NASA TECHNICAL NOTE

NASA TN D-3150

~~62895~~

NASA TN D-3150

AMPTIAC



# AN ANALYSIS OF A CHARRING ABLATION THERMAL PROTECTION SYSTEM

*by Donald M. Curry*

*Manned Spacecraft Center*
*Houston, Texas*



NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • DECEMBER 1965

NASA TN D-3150

# AN ANALYSIS OF A CHARRING ABLATION THERMAL PROTECTION SYSTEM

By Donald M. Curry

Manned Spacecraft Center
Houston, Texas

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151 – Price $4.00

# AN ANALYSIS OF A CHARRING ABLATION THERMAL PROTECTION SYSTEM

By Donald M. Curry
Manned Spacecraft Center

## SUMMARY

An analytical model is presented for predicting the transient one- TP dimensional thermal performance of a charring-ablator heat-protection system when exposed to a hyperthermal environment. The heat-protection system is considered to consist of an ablation material and backup structure. The ablating material is further considered to consist of three distinct regions or zones: char, reacting, and virgin material.

A FORTRAN IV digital computer program (STAB II) utilizing an implicit finite difference formulation has been written for the IBM 7094/40 computer system. The program considers one ablating material and a maximum of 12 back-up materials with conduction or radiation and/or convection allowed between materials. Thermal properties of all materials are temperature dependent, with the properties of the charring material also being state dependent.

The governing differential equations and their implicit finite difference formulation are presented. The program input and output are described in detail. The FORTRAN program statements and nomenclature are presented. Also, the theoretical and experimental results are compared. end

## INTRODUCTION

The analysis and design of thermal protection systems for entry into an atmospheric environment have resulted in a voluminous amount of literature on the general subject of ablation. (See refs. 1 and 2 for a survey of information on ablation.) The ablation materials may generally be classified into three categories: subliming, melting and vaporizing, and charring. The charring ablator normally provides the most efficient thermal-protection shield for the major portion of a manned entry vehicle. This report describes a method for predicting the thermal response of a typical charring-ablation material. The response of a charring material to a hyperthermal environment is extremely complex, and the mathematical model presented to analyze the transient behavior of the material contains simplifying assumptions and approximations necessary to afford even a numerical solution.

end

The equations derived in this analysis have been programmed in FORTRAN IV for an IBM 7094/40 computer system. The numerical formulation of this digital program, designated STAB II, is such that an implicit solution is obtained. The thermal response of a typical charring material as predicted by STAB II is compared with arc tunnel results.

A sample problem is presented in appendix A. Program usage instructions, including definitions of the input terminology, are presented in appendix B. Appendixes C and D are the program FORTRAN IV statements and definitions of the program terminology. A general flow chart of the program is presented in appendix E.

## SYMBOLS

| | |
|---|---|
| $A$ | collision frequency |
| $c_p$ | specific heat |
| $E$ | activation energy |
| $F$ | exterior view factor |
| $F_{env}$ | view factor—emissivity product to cabin environment |
| $H_d$ | heat of virgin material degradation |
| $H_T$ | total enthalpy |
| $H_w$ | wall enthalpy |
| $H_{300}$ | enthalpy of air at $300^\circ$ K |
| $h$ | film coefficient between backup materials |
| $h_{env}$ | film coefficient between last backup material and cabin environment |
| $k$ | thermal conductivity |
| $\dot{m}_c$ | mass loss rate of char material |
| $\dot{m}_g$ | gas ablation rate |
| NP | number of nodes in ablation material |

| | |
|---|---|
| $n$ | order of reaction |
| $Q_{in.}$ | net heat rate into front surface |
| $\dot{q}_{c\ blow}$ | hot wall convective heat flux with blowing |
| $\dot{q}_{comb}$ | heat flux due to combustion |
| $\dot{q}_{cw}$ | cold wall convective heat flux without blowing |
| $\dot{q}_{rad}$ | radiation heat flux |
| $R$ | universal gas constant |
| $S$ | surface recession depth |
| $\dot{S}$ | surface recession rate |
| $T$ | temperature of node at beginning of time step |
| $T_{env}$ | cabin environment temperature |
| $T'$ | temperature of node at end of time step |
| $T_{\infty}$ | radiation heat sink temperature |
| VL | thickness of ablation material |
| $X$ | distance from surface to any point |
| $\Delta H_c$ | heat of combustion per unit weight of char |
| $\Delta X$ | thickness of a node |
| $\Delta\theta$ | time step $(\theta' - \theta)$ |
| $\epsilon$ | emissivity of material |
| $\eta$ | transpiration cooling efficiency |
| $\theta$ | initial time |
| $\theta'$ | final time |
| $\xi$ | transform for the ablation material |

$\rho$ density

$\sigma$ Stefan-Boltzmann constant

$\psi$ blocking effectiveness function

Subscripts:

c charred state

i node number

j material number

v virgin state

## PROGRAM DESCRIPTION

The following general requirements were established before writing a digital computer program to analyze a charring ablation system:

(1) Stability of the equations for all applications.

(2) Machine running time short enough to make use of the program economically feasible (a minimum of turn around time per problem).

(3) A minimum of input per problem.

(4) A wide variety of boundary conditions for application to both trajectory data and ground or flight test data analysis.

STAB II has been formulated in FORTRAN IV to analyze the transient thermal performance of a charring ablator heat protection system. The program considers one ablating material and up to 12 different backup materials with or without air gaps. Pure conduction or radiation and/or convection between backup materials is allowed. The ablation material may be divided into a maximum of 50 nodes, and each backup material may be subdivided into a maximum of 10 nodes. The thermal properties of the materials are in tabular form and are temperature dependent. The ablation material is also dependent upon its state, that is, fully charred, partially charred, et cetera.

The following surface boundary condition options are provided:

(1) Cold-wall convective and radiative heat flux tables as a function of time. These components are specified separately, since mass transfer at the surface blocks part of the convective heating but, in general, has no effect on the radiant heating.

(2) Surface temperature as a function of time.

(3) Surface recession as a function of temperature <u>or</u> time. Surface recession as a function of temperature and pressure is also available.

Heat loss to the interior environment for the last node of the backup structure can be specified by two methods:

(1) Conduction into the node and radiation and/or convection loss to the interior environment.

(2) Conduction into the node and adiabatic wall.

The STAB II numerical formulation of the equations describing the response of the heat shield is such that an implicit solution has been obtained. It is well known that numerical solutions of partial differential equations are subject to several different types of errors. The first of these is the truncation error, due to the use of a finite subdivision. This error may be reduced by simply choosing a smaller subdivision, $\Delta X$. The exact values are approached more and more closely as $\Delta X$ decreases. The second kind of error is the numerical, or roundoff error. The way in which this numerical error grows or decays with time determines the stability of the difference equations.

To illustrate the differences in the explicit and implicit equation form, consider a nonablating homogeneous solid. The one-dimensional Fourier conduction equation, neglecting any heat generation terms, is

$$\frac{\partial}{\partial X}\left(k\frac{\partial T}{\partial X}\right) = \rho c_p \frac{\partial T}{\partial \theta} \tag{1}$$

The finite difference form of equation (1) written in the conventional forward time step or explicit form for the $i^{th}$ node is

$$\frac{\left(T_{i-1} - T_i\right)}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}} - \frac{\left(T_i - T_{i+1}\right)}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}} = \rho c_p \frac{\Delta X\left(T_i' - T_i\right)}{\Delta \theta} \tag{2}$$

where the prime superscript denotes values at the end of the time step

$$\Delta\theta = \theta' - \theta$$

For explicit conduction solutions, the following stability criterion has been established:

$$\frac{\rho c_p}{k}\frac{(\Delta X)^2}{\Delta\theta} \geq 2$$

which places an upper limit on the time step $\Delta\theta$ for a fixed truncation error. This criterion can require a prohibitive amount of machine time.

Liebmann (ref. 3) advocated a solution of the equation which does not require this stability criterion. The finite difference equations are written in a backward time step form which affords an implicit solution.

The implicit (backward time step) difference form of equation (1) for the $i^{th}$ node is:

$$\frac{\left(T'_{i-1} - T'_i\right)}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}} - \frac{\left(T'_i - T'_{i+1}\right)}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}} = \rho c_p \frac{\Delta X\left(T'_i - T_i\right)}{\Delta\theta} \tag{3}$$

Equation (3) uses the temperature differences at the end of the finite time interval instead of the beginning, as in the explicit method of equation (2). The only known temperature in equation (3) is $T_i$, but there are corresponding equations for each point in the system, and all are solved simultaneously to yield the temperature at each node.

Collecting all unknown temperatures on the left side of the equation and the known temperature on the right side, equation (3) becomes

$$\left(\frac{1}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}}\right)T'_{i-1} - \left(\frac{1}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}} + \frac{1}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}}\right.$$

$$\left. + \frac{\rho_i c_{p_i} \Delta X}{\Delta\theta}\right)T'_i + \left(\frac{1}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}}\right)T'_{i+1} = -\left(\frac{\rho_i c_{p_i} \Delta X}{\Delta\theta}\right)T_i \tag{4}$$

Equation (4) is of the form

$$AT'_{i-1} + BT'_i + CT'_{i+1} = D \tag{5}$$

STAB II generates such an equation for each node in the system.

Since radiation is an important mode of heat transfer in charring ablative systems, a problem is encountered in any equation containing a radiation term. The radiation heat flux, written in a backward difference form is:

$$\dot{q}_{rad} = F\epsilon\sigma\left({T'_i}^4 - {T_\infty}^4\right) \tag{6}$$

This term cannot be used in an implicit solution since the unknown temperature $T_i'$ is to be the 4th power. The 4th power unknown can be eliminated by the following linearizations:

$$\left(T_i'\right)^4 = \left(T_i + \Delta T\right)^4 = T_i^{\ 4}\left(1 + \frac{\Delta T}{T_i}\right)^4 \tag{7}$$

where

$$\Delta T = T_i' - T_i$$

let

$$Z \equiv \frac{\Delta T}{T_i}$$

and rewrite equation (7) as

$$\left(T_i'\right)^4 = \left(T_i\right)^4 (1 + Z)^4 \tag{8}$$

If $Z$ has an absolute value near zero, the following is true

$$(1 + Z)^4 \cong 1 + 4Z \tag{9}$$

Now substituting equation (9) into equation (8)

$$\left(T_i'\right)^4 \cong \left(T_i\right)^4 (1 + 4Z) = \left(T_i\right)^4 \left(1 + 4\,\frac{\Delta T}{T_i}\right)$$

$$\cong 4T_i^{\ 3}T_i' - 3T_i^{\ 4} \tag{10}$$

Equation (10) is a linearized approximation of equation (7) in which the unknown temperature is only to the first power. The assumption in equation (10) is that $\Delta T/T_i$ has an absolute value near zero. Figure 1 is a plot of the error obtained when $(1 + 4Z)$ is substituted for $(1 + Z)^4$. For most ablation problems in which the surface temperature is high and the radiation losses are significant, the value of $\Delta T/T_i$ can easily be controlled to values of less than $\pm 0.1$.

Therefore, equation (6) can now be written

$$\dot{q}_{rad} = F\epsilon\sigma\left(4T_i^{\ 3}T_i' - 3T_i^{\ 4} - T_\infty^{\ 4}\right) \tag{11}$$

Using the linearized approximation for the radiation terms, the resulting system of implicit difference equations constitute a tridiagonal matrix of the following form:

$$
\begin{aligned}
B_1T_1 + C_1T_2 \qquad\qquad\qquad\qquad &= D_1 \\
A_2T_1 + B_2T_2 + C_2T_3 \qquad\qquad &= D_2 \\
A_3T_2 + B_3T_3 + C_3T_4 \qquad &= D_3 \\
\vdots \qquad \vdots \qquad\qquad &\;\;\vdots \\
A_NT_{N-1} + B_NT_N &= D_N
\end{aligned}
$$

Gauss' elimination method, discussed in reference 4, is applied to solve the system of equations. This method affords a fast and accurate solution for matrices containing a dominant diagonal. The solution of this matrix gives the temperature of each node in the system for the next future time step. The entire process is repeated for each time step throughout the run, giving a time history of the temperature at each node.

Using this method of solution, residual errors in the temperature computations at the beginning of the time step are distributed throughout the entire system of nodal equations and tend to cancel out rapidly. The principal advantage in using the implicit method is a set of equations that are mathematically stable in time and distance. Therefore, the magnitude of the time step is not limited by a convergence criterion. However, care must be taken in selecting the magnitude of the time step in order to minimize truncation errors when the second derivative of temperature with respect to time is large. A similar approach is used to minimize truncation errors in distance by choosing small node dimensions in locations where large second derivatives of temperature with respect to distance are expected.

In the case of a char-forming ablative heat shield where approximately 80 percent of the heat is reradiated, instability can arise in taking large time steps. The temperature of the surface node can start oscillating on successive time steps when a balance between the radiation source and the heat sink has been achieved. Therefore, in ablation problems in which the surface node loses a large percentage of heat by radiation, oscillations of the node can be damped out by taking small time steps during conditions of high heat flux and near radiation equilibrium temperatures.

## ANALYSIS

Figure 2 is a schematic of the thermal protection system to be analyzed. A receding surface has been assumed with the formation of a residual char layer and reaction zone. The thermal protection system is composed of one charring material and a maximum of 12 different backup materials with or without air gaps.

The analysis is such that the entire system may be composed of noncharring materials. The thermal properties of all materials are temperature dependent; also, the charring material properties are state dependent (fully or partially charred).

The response of charring ablation heat shields to a hyperthermal environment is extremely complex, and simplifying assumptions and approximations are necessary to afford a numerical solution. The following assumptions and approximations are utilized in the equations developed in this report:

(1) The material decomposes from the virgin state to a porous char layer in the reaction zone.

(2) The reaction zone can be defined by an upper and lower temperature limit.

(3) The gas generated within the reaction zone is assumed to pass out of the structure with no pressure loss. No gas accumulation within a node is allowed.

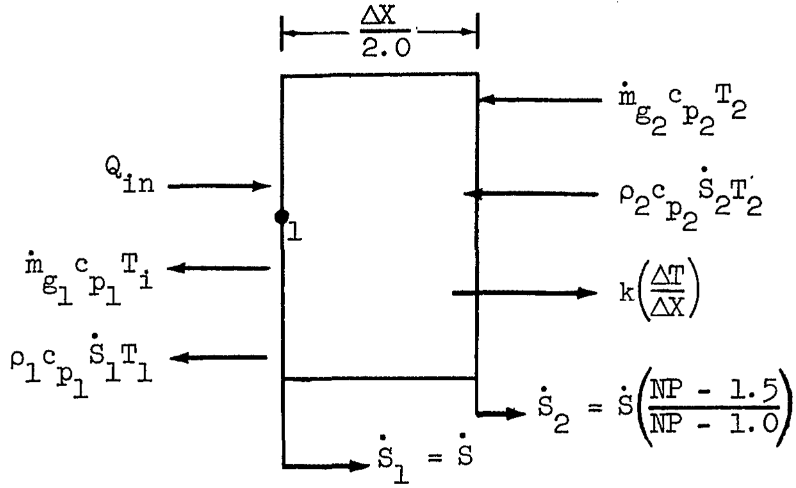
(4) Local thermal equilibrium is maintained between the gas and porous char matrix.

(5) The gas undergoes no further chemical reaction within the residual material after having been formed.

## Derivation of Equations

The equations are derived for a moving boundary coordinate system, where the front face is the moving surface (ref. 5). With this system, the ablating material is divided into a fixed number of nodes of thickness $\Delta X$ which depends on the instantaneous location of the front face. The surface recession is handled in a continuous manner, eliminating the need of throwing away or lumping off of nodes.

The physical model for the front surface, including all heating terms, is shown as follows:




The energy equation at the front char surface is

$$\frac{d}{d\theta}\left(\frac{1}{2}\,\Delta X\;\rho_1 c_{p_1} T_1\right) = \frac{1}{2}\,\Delta X\;\rho_1 c_{p_1}\frac{dT_1}{d\theta} + \frac{1}{2}\,\rho_1 c_{p_1} T_1 \frac{d(\Delta X)}{d\theta}$$

$$= Q_{in} + \dot{m}_{g_2} c_{p_2} T_2' + \rho_2 \dot{S}_2 c_{p_2} T_2' - \dot{m}_{g_1} c_{p_1} T_1'$$

$$- \rho_1 c_{p_1} \dot{S}_1 T_1' - k_{1\text{-}2}\left(\frac{\Delta T}{\Delta X}\right) \tag{12}$$

where

$$Q_{in} = \dot{q}_{c,\ blow} + \dot{q}_{rad} + \dot{q}_{comb} - F\epsilon\sigma\left(T_1^{\ 4} - T_\infty^{\ 4}\right)$$

and

$$\frac{d(\Delta X)}{d\theta} = \frac{d}{d\theta}\left(\frac{VL - S}{NP - 1}\right) = -\frac{\dot{S}}{NP - 1}$$

where $\dot{S}$ is the linear surface recession rate and NP is the total number of nodes in the ablation material of thickness VL.

Rewriting equation (12) in implicit finite difference form

$$Q_{in} + \dot{m}_{g_2} c_{p_2} T_2' - \dot{m}_{g_1} c_{p_1} T_1' - \dot{S}\rho_1 c_{p_1} T_1' - \frac{\left(T_1' - T_2'\right)}{\frac{\Delta X}{2k_1} + \frac{\Delta X}{2k_2}}$$

$$+ \rho_2 c_{p_2} \dot{S} \left(\frac{NP - 1.5}{NP - 1.0}\right) T_2' = \rho_1 c_{p_1} \frac{\Delta X}{2}\left(\frac{T_1' - T_1}{\Delta\theta}\right)$$

$$- \frac{1}{2}\rho_1 c_{p_1} T_1' \left(\frac{\dot{S}}{NP - 1}\right) \tag{12a}$$

Then, rearranging and collecting terms yield

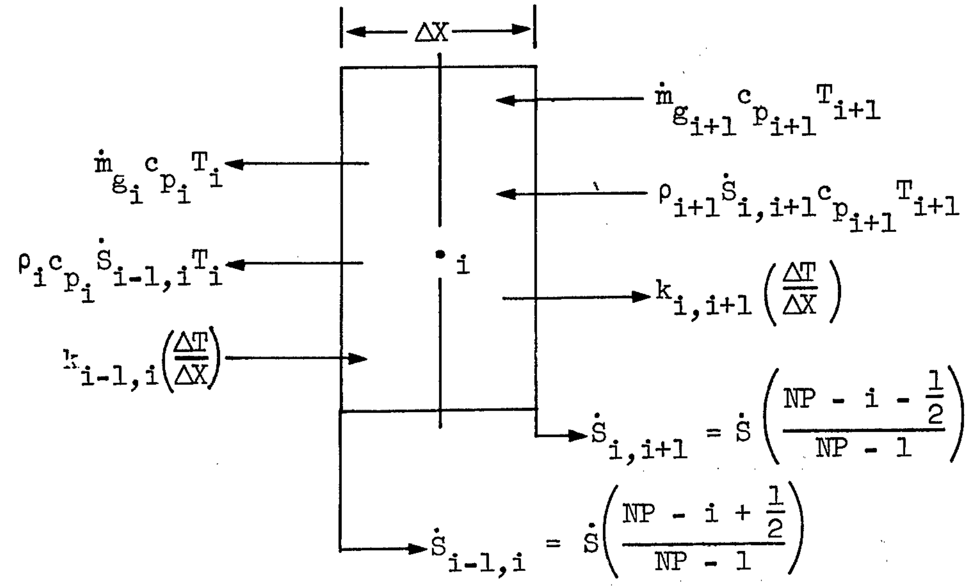
$$- \left[\dot{m}_{g_1} c_{p_1} + \dot{S}\rho_1 c_{p_1} + \rho_1 c_{p_1} \frac{\Delta X}{2\Delta\theta} + \frac{1}{\frac{\Delta X}{2k_1} + \frac{\Delta X}{2k_2}} - \frac{1}{2}\rho_1 c_{p_1} \left(\frac{\dot{S}}{NP - 1}\right)\right] T_1'$$

$$+ \left[\dot{m}_{g_2} c_{p_2} + \frac{1}{\frac{\Delta X}{2k_1} + \frac{\Delta X}{2k_2}} + \rho_2 c_{p_2} \dot{S} \left(\frac{NP - 1.5}{NP - 1.0}\right)\right] T_2'$$

$$= -\rho_1 c_{p_1} \frac{\Delta X}{2\Delta\theta} T_1 - Q_{in}.$$

(12b)

The physical model for interior points in the mature char zone, including all heating terms, is shown in the following sketch:




The energy equation for interior points in the char matrix is

$$\frac{d}{d\theta}\left(\Delta X_i \rho_i c_{p_i} T_i\right) = \Delta X \rho_i c_{p_i} \frac{dT_i}{d\theta} - \rho_i c_{p_i} T_i' \left(\frac{\dot{S}}{NP - 1}\right)$$

$$= \dot{m}_{g_{i+1}} c_{p_{i+1}} T_{i+1}' + k_{i-1,i}\left(\frac{\Delta T}{\Delta X}\right) + \rho_{i+1} c_{p_{i+1}} \dot{S} \left(\frac{NP - i - \frac{1}{2}}{NP - 1}\right) T_{i+1}'$$

$$- k_{i,i+1}\left(\frac{\Delta T}{\Delta X}\right) - \dot{m}_{g_i} c_{p_i} T_i' - \rho_i c_{p_i} \dot{S} \left(\frac{NP - i + \frac{1}{2}}{NP - 1}\right) T_i' \qquad (13)$$

Putting equation (13) in an implicit finite difference form yields

$$\left(\frac{1}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}}\right)T'_{i-1} - \left[\dot{m}_{g_i} c_{p_i} + \rho_i c_{p_i} \dot{S}\left(\frac{NP - i + \frac{1}{2}}{NP - 1}\right) + \frac{1}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}}\right.$$

$$\left. + \frac{1}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}} + \rho_i c_{p_i} \frac{\Delta X}{\Delta\theta} - \rho_i c_{p_i}\left(\frac{\dot{S}}{NP - 1}\right)\right] T'_i$$

$$+ \left[\dot{m}_{g_{i+1}} c_{p_{i+1}} + \frac{1}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}} + \rho_{i+1} c_{p_{i+1}} \dot{S}\left(\frac{NP - i - \frac{1}{2}}{NP - 1}\right)\right] T'_{i+1}$$

$$= -\rho_i c_{p_i} \frac{\Delta X}{\Delta\theta} T_i \tag{13a}$$

In the mature char zone, no internal gaseous ablation products are assumed to form. The reaction zone is the source for the formation of the internal gaseous products. Therefore, in equations (12) and (13), $\dot{m}_{g_i} = \dot{m}_{g_{i+1}}$

The physical model for nodes in the reaction zone is identical to schematic shown for the interior nodes in the char except for considering the energy absorbed in formation of the gaseous ablation products. The heat balance equation for a node in the reaction zone is

$$\frac{d}{d\theta}\left(\Delta X \rho_i c_{p_i} T_i\right) = \Delta X \rho_i c_{p_i} \frac{dT_i}{d\theta} - \rho_i c_{p_i} T'_i \left(\frac{\dot{S}}{NP - 1}\right) - \left(\dot{m}_{g_i} - \dot{m}_{g_{i+1}}\right) H_d$$

$$= \dot{m}_{g_{i+1}} c_{p_{i+1}} T'_{i+1} + k_{i-1,i}\left(\frac{\Delta T}{\Delta X}\right) + \rho_{i+1} c_{p_{i+1}} \dot{S}\left(\frac{NP - i - \frac{1}{2}}{NP - 1}\right) T'_{i+1}$$

$$- k_{i,i+1}\left(\frac{\Delta T}{\Delta X}\right) - \dot{m}_{g_i} c_{p_i} T'_i - \rho_i c_{p_i} \dot{S}\left(\frac{NP - i + \frac{1}{2}}{NP - 1}\right) T'_i \tag{14}$$

Rearranging,

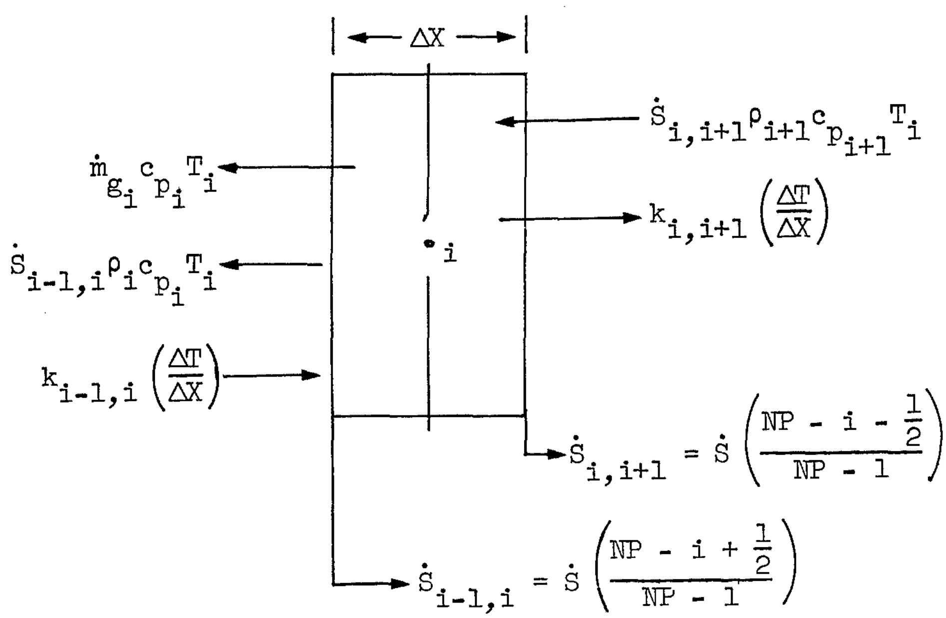
$$\left(\frac{1}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}}\right) T'_{i-1} - \left[\dot{m}_{g_i} c_{p_i} + \rho_i c_{p_i} \dot{S}\left(\frac{NP - i + \frac{1}{2}}{NP - 1}\right) + \frac{1}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}}\right.$$

$$\left. + \frac{1}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}} + \rho_i c_{p_i} \frac{\Delta X}{\Delta\theta} - \rho_i c_{p_i}\left(\frac{\dot{S}}{NP - 1}\right)\right] T'_i + \left[\dot{m}_{g_{i+1}} c_{p_{i+1}}\right.$$

$$\left. + \frac{1}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}} + \rho_{i+1} c_{p_{i+1}} \dot{S}\left(\frac{NP - i - \frac{1}{2}}{NP - 1}\right)\right] T'_{i+1}$$

$$= -\rho_i c_{p_i} \frac{\Delta X}{\Delta\theta} T_i - \left(\dot{m}_{g_i} - \dot{m}_{g_{i+1}}\right) H_d \qquad (14a)$$

The physical model for the interface between the reaction zone and virgin material is illustrated as follows:



The heat balance equation for this node is

$$\frac{d}{d\theta}\left(\Delta X \rho_i c_{p_i} T_i\right) = \Delta X \rho_i c_{p_i} \frac{dT_i}{d\theta} - \rho_i c_{p_i} T_i'\left(\frac{\dot{S}}{NP - 1}\right) - \dot{m}_{g_i} H_d$$

$$= k_{i-1,i}\left(\frac{\Delta T}{\Delta X}\right) + \rho_{i+1} c_{p_{i+1}} \dot{S}\left(\frac{NP - i - \frac{1}{2}}{NP - 1}\right) T_{i+1}'$$

$$- k_{i,i+1}\left(\frac{\Delta T}{\Delta X}\right) - \dot{m}_{g_i} c_{p_i} T_i' - \rho_i c_{p_i} \dot{S}\left(\frac{NP - i + \frac{1}{2}}{NP - 1}\right) T_i' \tag{15}$$

Rearranging yields

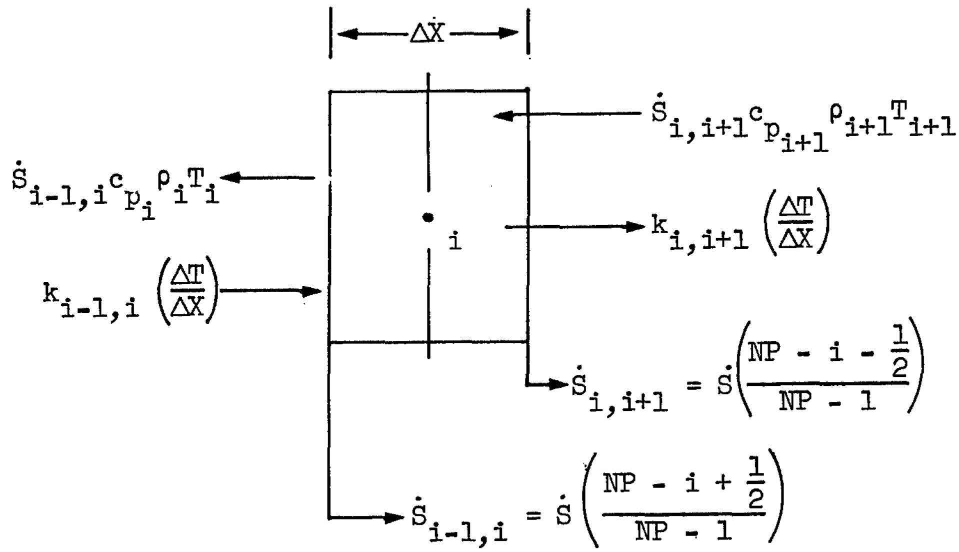
$$\left(\frac{1}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}}\right) T_{i-1}' - \left[\dot{m}_{g_i} c_{p_i} + \frac{1}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}} + \frac{1}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}}\right.$$

$$\left. + \rho_i c_{p_i} \dot{S}\left(\frac{NP - i + \frac{1}{2}}{NP - 1}\right) + \rho_i c_{p_i} \frac{\Delta X}{\Delta\theta} - \rho_i c_{p_i}\left(\frac{\dot{S}}{NP - 1}\right)\right] T_i'$$

$$+ \left[\frac{1}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}} + \rho_{i+1} c_{p_{i+1}} \dot{S}\left(\frac{NP - i - \frac{1}{2}}{NP - 1}\right)\right] T_{i+1}'$$

$$= -\rho_i c_{p_i} \frac{\Delta X}{\Delta\theta} T_i - \dot{m}_{g_i} H_d \tag{15a}$$

The physical model for an interior node in the virgin material is




The heat balance for this nonablating node is

$$\frac{d}{d\theta}\left(\Delta X \rho_i c_{p_i} T_i\right) = \Delta X \rho_i c_{p_i} \frac{dT_i}{d\theta} - \rho_i c_{p_i} T_i' \left(\frac{\dot{S}}{NP - 1}\right)$$

$$= k_{i-1,i}\left(\frac{\Delta T}{\Delta X}\right) + \rho_{i+1} c_{p_{i+1}} \dot{S}\left(\frac{NP - i - \frac{1}{2}}{NP - 1}\right) T_{i+1}' - k_{i,i+1}\left(\frac{\Delta T}{\Delta X}\right)$$

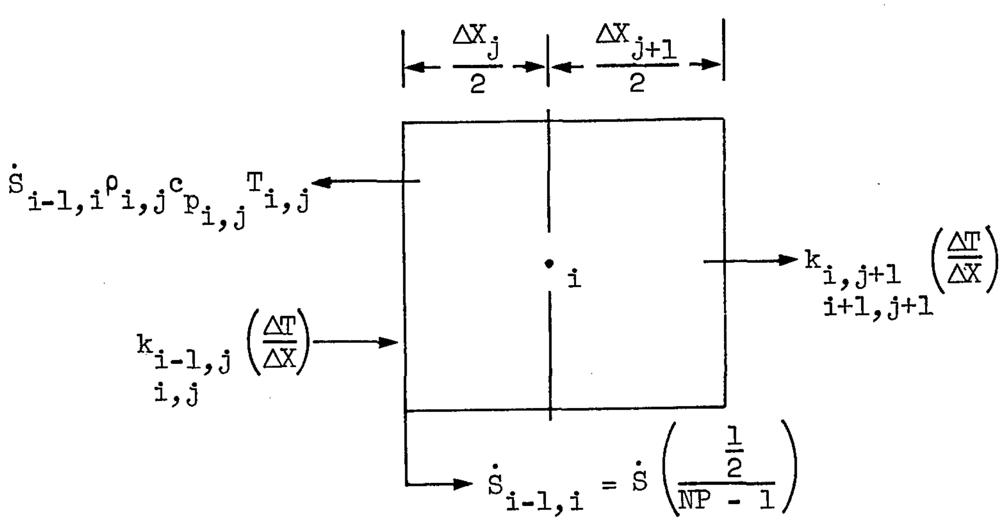
$$- \rho_i c_{p_i} \dot{S}\left(\frac{NP - i + \frac{1}{2}}{NP - 1}\right) T_i' \qquad (16)$$

Rearranging,

$$\left(\frac{1}{\frac{\Delta X}{2k_{i-1}}+\frac{\Delta X}{2k_i}}\right)T'_{i-1} - \left[\frac{1}{\frac{\Delta X}{2k_{i-1}}+\frac{\Delta X}{2k_i}} + \frac{1}{\frac{\Delta X}{2k_i}+\frac{\Delta X}{2k_{i+1}}} + \rho_i c_{p_i}\dot{S}\left(\frac{NP - i + \frac{1}{2}}{NP - 1}\right) + \rho_i c_{p_i}\frac{\Delta X}{\Delta\theta} - \rho_i c_{p_i}\left(\frac{\dot{S}}{NP - 1}\right)\right]T'_i$$

$$+ \left[\frac{1}{\frac{\Delta X}{2k_i}+\frac{\Delta X}{2k_{i+1}}} + \rho_{i+1}c_{p_{i+1}}\dot{S}\left(\frac{NP - i - \frac{1}{2}}{NP - 1}\right)\right]T'_{i+1} = -\rho_i c_{p_i}\frac{\Delta X}{\Delta\theta}T_i \qquad (16a)$$

The physical model for the last node in the ablation material and first node in the backup structure is




For this interface, $T'_{i,j} = T'_{i,j+1}$.

The heat balance equation for this node is

$$\frac{d}{d\theta}\left[\left(\frac{\Delta X_j}{2}\,\rho_{i,j}c_{p_{i,j}} + \frac{\Delta X_{j+1}}{2}\,c_{p_{i,j+1}}\rho_{i,j+1}\right)T_i\right]$$

$$= \left(\frac{\Delta X_j\rho_{i,j}c_{p_{i,j}} + \Delta X_{j+1}c_{p_{i,j+1}}\rho_{i,j+1}}{2}\right)\frac{dT_i}{d\theta} - \frac{1}{2}\left(\frac{\dot{S}}{NP - 1}\right)c_{p_{i,j}}\rho_{i,j}T'_i$$

$$= k_{\substack{i-1,j\\i,j}}\left(\frac{\Delta T}{\Delta X}\right) - c_{p_{i,j}}\rho_{i,j}\dot{S}\left(\frac{\frac{1}{2}}{NP - 1}\right)T'_i - k_{\substack{i,j+1\\i+1,j+1}}\left(\frac{\Delta T}{\Delta X}\right) \tag{17}$$

Rearranging yields

$$\left(\frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}}\right)T'_{i-1} - \left[\frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} + \frac{1}{\frac{\Delta X_{j+1}}{2k_{i,j+1}} + \frac{\Delta X_{j+1}}{2k_{i+1,j+1}}}\right.$$

$$\left.+\left(\frac{\Delta X_j\rho_{i,j}c_{p_{i,j}} + \Delta X_{j+1}c_{p_{i,j+1}}\rho_{i,j+1}}{2\Delta\theta}\right)\right]T'_i + \left(\frac{1}{\frac{\Delta X_{j+1}}{2k_{i,j+1}} + \frac{\Delta X_{j+1}}{2k_{i+1,j+1}}}\right)T'_{i+1}$$

$$= -\left(\frac{\Delta X_j c_{p_{i,j}}\rho_{i,j} + \Delta X_{j+1}c_{p_{i,j+1}}\rho_{i,j+1}}{2\Delta\theta}\right)T_i \tag{17a}$$

The backup structure may contain up to a maximum of 12 different materials with or without air gaps between materials. Therefore, conduction or radiation and/or convection between materials is allowed. The heat balance equations for the various modes of heat transfer in the backup structure are presented in the following equations:

(1) Interior node material:

$$\frac{\left(T'_{i-1,j} - T'_{i,j}\right)}{\dfrac{\Delta X_j}{2k_{i-1,j}} + \dfrac{\Delta X_j}{2k_{i,j}}} - \frac{\left(T'_{i,j} - T'_{i+1,j}\right)}{\dfrac{\Delta X_j}{2k_{i,j}} + \dfrac{\Delta X_j}{2k_{i+1,j}}} = \rho_{i,j} c_{p_{i,j}} \frac{\Delta X_j}{\Delta \theta} \left(T'_{i,j} - T_{i,j}\right) \qquad (18)$$

Rearranging, equation (18) becomes

$$\left(\frac{1}{\dfrac{\Delta X_j}{2k_{i-1,j}} + \dfrac{\Delta X_j}{2k_{i,j}}}\right) T'_{i-1,j} - \left(\frac{1}{\dfrac{\Delta X_j}{2k_{i-1,j}} + \dfrac{\Delta X_j}{2k_{i,j}}} + \frac{1}{\dfrac{\Delta X_j}{2k_{i,j}} + \dfrac{\Delta X_j}{2k_{i+1,j}}}\right.$$

$$\left. + \rho_{i,j} c_{p_{i,j}} \frac{\Delta X_j}{\Delta \theta}\right) T'_{i,j} + \left(\frac{1}{\dfrac{\Delta X_j}{2k_{i,j}} + \dfrac{\Delta X_j}{2k_{i+1,j}}}\right) T'_{i+1,j}$$

$$= -\rho_{i,j} c_{p_{i,j}} \frac{\Delta X_j}{\Delta \theta} T_{i,j} \qquad (18a)$$

(2) <u>First</u> and <u>last</u> nodes of two interior materials with <u>no</u> gap:

$$\frac{\left(T'_{i-1,j} - T'_{i,j}\right)}{\dfrac{\Delta X_j}{2k_{i-1,j}} + \dfrac{\Delta X_j}{2k_{i,j}}} - \frac{\left(T'_{i,j+1} - T'_{i+1,j+1}\right)}{\dfrac{\Delta X_{j+1}}{2k_{i,j+1}} + \dfrac{\Delta X_{j+1}}{2k_{i+1,j+1}}}$$

$$= \left(\frac{\rho_{i,j} c_{p_{i,j}} \Delta X_j + \rho_{i,j+1} c_{p_{i,j+1}} \Delta X_{j+1}}{2\,\Delta\theta}\right) \left(T'_{i,j} - T_{i,j}\right) \qquad (19)$$

For this case, $T'_{i,j} = T'_{i,j+1}$

Rearranging, equation (19) becomes

$$\left(\frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}}\right) T'_{i-1,j} - \left[\frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} + \frac{1}{\frac{\Delta X_{j+1}}{2k_{i,j+1}} + \frac{\Delta X_{j+1}}{2k_{i+1,j+1}}}\right.$$

$$\left. + \left(\frac{\rho_{i,j} c_{p_{i,j}} \Delta X_j + \rho_{i,j+1} c_{p_{i,j+1}} \Delta X_{j+1}}{2\,\Delta\theta}\right)\right] T'_{i,j}$$

$$+ \left(\frac{1}{\frac{\Delta X_{j+1}}{2k_{i,j+1}} + \frac{\Delta X_{j+1}}{2k_{i+1,j+1}}}\right) T'_{i+1,j+1}$$

$$= - \left(\frac{\rho_{i,j} c_{p_{i,j}} \Delta X_j + c_{p_{i,j+1}} \rho_{i,j+1} \Delta X_{j+1}}{2\,\Delta\theta}\right) T_{i,j} \tag{19a}$$

(3) <u>First node</u> of interior material <u>with an air gap</u> between materials:

$$h_j\left(T'_{i-1,j} - T'_{i,j+1}\right) + \left(\frac{\sigma}{\frac{1}{\epsilon_j} + \frac{1}{\epsilon_{j+1}} - 1}\right)\left({T'}^{4}_{i-1,j} - {T'}^{4}_{i,j+1}\right)$$

$$- \left(\frac{T'_{i,j+1} - T'_{i+1,j+1}}{\frac{\Delta X_{j+1}}{2k_{i,j+1}} + \frac{\Delta X_{j+1}}{2k_{i+1,j+1}}}\right) = \frac{\rho_{i,j+1} c_{p_{i,j+1}} \Delta X_{j+1}}{2\,\Delta\theta}\left(T'_{i,j+1} - T_{i,j+1}\right) \tag{20}$$

Equation (20) may be linearized by using the approximation

$$T'^4 \cong 4T^3T' - 3T^4$$

as discussed in the Program Description section.

Therefore, rearranging and linearizing, equation (20) becomes

$$\left[h_j + \left(\frac{4\sigma T^3_{i-1,j}}{\frac{1}{\epsilon_j} + \frac{1}{\epsilon_{j+1}} - 1}\right)\right] T'_{i-1,j} - \left[h_j + \left(\frac{4\sigma T^3_{i,j+1}}{\frac{1}{\epsilon_j} + \frac{1}{\epsilon_{j+1}} - 1}\right)\right.$$

$$\left. + \frac{1}{\frac{\Delta X_{j+1}}{2k_{i,j+1}} + \frac{\Delta X_{j+1}}{2k_{i+1,j+1}}} + \frac{\rho_{i,j+1} c_{p_{i,j+1}} \Delta X_{j+1}}{2\,\Delta\theta}\right] T'_{i,j+1}$$

$$+ \left(\frac{1}{\frac{\Delta X_{j+1}}{2k_{i,j+1}} + \frac{\Delta X_{j+1}}{2k_{i+1,j+1}}}\right) T'_{i+1,j+1} = - \frac{\rho_{i,j+1} c_{p_{i,j+1}} \Delta X_{j+1}}{2\,\Delta\theta} T_{i,j+1}$$

$$- \left(\frac{3\sigma}{\frac{1}{\epsilon_j} + \frac{1}{\epsilon_{j+1}} - 1}\right)\left(T^4_{i,j+1} - T^4_{i-1,j}\right) \qquad (20a)$$

(4) <u>Last node</u> of an interior material <u>with an air gap</u> between materials:

$$\frac{\left(T'_{i-1,j} - T'_{i,j}\right)}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} - h_j\left(T'_{i,j} - T'_{i,j+1}\right)$$

$$- \left(\frac{\sigma}{\frac{1}{\epsilon_j} + \frac{1}{\epsilon_{j+1}} - 1}\right)\left(T'^{4}_{i,j} - T'^{4}_{i,j+1}\right) = \frac{\rho_{i,j} c_{p_{i,j}} \Delta X_j}{2\,\Delta\theta} \left(T'_{i,j} - T_{i,j}\right) \qquad (21)$$

Rearranging and linearizing, equation (21) becomes

$$\left(\frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}}\right)T'_{i-1,j} - \left[ h_j + \frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} + \left(\frac{4\sigma T^3_{i,j}}{\frac{1}{\epsilon_j} + \frac{1}{\epsilon_{j+1}} - 1}\right) + \frac{\rho_{i,j} c_{p_{i,j}} \Delta X_j}{2\,\Delta\theta}\right] T'_{i,j} + \left[ h_j + \left(\frac{4\sigma T^3_{i,j+1}}{\frac{1}{\epsilon_j} + \frac{1}{\epsilon_{j+1}} - 1}\right)\right] T'_{i,j+1}$$

$$= - \frac{\rho_{i,j} c_{p_{i,j}} \Delta X_j}{2\,\Delta\theta} T_{i,j} + \left(\frac{3\sigma}{\frac{1}{\epsilon_j} + \frac{1}{\epsilon_{j+1}} - 1}\right)\left(T^4_{i,j+1} - T^4_{i,j}\right) \tag{21a}$$

(5) Final node in backup structure:

(a) Adiabatic surface –

$$\frac{T'_{i-1,j} - T'_{i,j}}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} = \frac{\rho_{i,j} c_{p_{i,j}} \Delta X_j}{2\,\Delta\theta}\left(T'_{i,j} - T_{i,j}\right) \tag{22}$$

Rearranging, equation (22) becomes

$$\left(\frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}}\right)T'_{i-1,j} - \left(\frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} + \frac{\rho_{i,j} c_{p_{i,j}} \Delta X_j}{2\,\Delta\theta}\right) T'_{i,j} = - \frac{\rho_{i,j} c_{p_{i,j}} \Delta X_j}{2\,\Delta\theta} T_{i,j} \tag{22a}$$

(b) Radiation and/or convection loss to cabin environment –

$$\left(\frac{T'_{i-1,j} - T'_{i,j}}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}}\right) - h_{env}\left(T'_{i,j} - T_{env}\right)$$

$$- F_{env}\sigma\left(T'^{4}_{i,j} - T^{4}_{env}\right) = \frac{\rho_{i,j}c_{p_{i,j}}\Delta X_j}{2\,\Delta\theta}\left(T'_{i,j} - T_{i,j}\right) \qquad (23)$$

Rearranging, equation (23) becomes

$$\left(\frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}}\right)T'_{i-1,j} - \left(h_{env} + \frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} + F_{env}\sigma 4T^{3}_{i,j}\right.$$

$$\left. + \frac{\rho_{i,j}c_{p_{i,j}}\Delta X_j}{2\,\Delta\theta}\right)T'_{i,j} = -\frac{\rho_{i,j}c_{p_{i,j}}\Delta X_j}{2\,\Delta\theta}T_{i,j}$$

$$- h_{env}T_{env} - F_{env}\sigma\left(3T^{4}_{i,j} + T^{4}_{env}\right) \qquad (23a)$$

## Discussion of Assumptions

A brief discussion of several assumptions and approximations made in deriving the heat balance equations is now presented.

As shown in the Derivation of Equations section, transient heat conduction, thermal degradation, and the flow of the gaseous products from the reaction zone are the internal thermal transport phenomena of interest. Several methods are available in the treatment of the thermal decomposition process, and they differ primarily in whether the chemical decomposition occurs in a single plane at a fixed temperature or whether a spacially continuous decomposition in depth is assumed. This analysis assumes that the decomposition from the virgin to the char state occurs in a reaction zone that is defined by known temperature limits. These temperature limits are determined from thermogravimetric test data for the particular material being investigated. Figure 3 is a thermogravimetric curve for typical charring ablation material. From this curve, the rate of pyrolysis $\dot{m}_g$ is calculated by knowing the

temperature change of a particular node with time, that is,

$$\dot{\rho}_i = \frac{\rho_i' - \rho_i}{\Delta\theta} \tag{24}$$

and

$$\dot{m}_{g_i} = \sum_{i}^{NP} \dot{\rho}_i \Delta X_i \tag{25}$$

This method of computing the gas-generation rates and local instantaneous density may be subject to error since the thermogravimetric curve of a material is influenced by temperature rise rate (deg/sec), and the reaction zone may shift up and down the temperature scale. This error can be eliminated by the use of an Arrhenius expression of the form

$$\frac{d\rho}{d\theta} = -A\left(\rho - \rho_c\right)^n e^{-\frac{E}{RT}} \tag{26}$$

The method now being used in STAB II (equation (25)) to calculate the pyrolysis rate is being investigated to determine its validity. The final formulation of the pyrolysis rate law must rest heavily on the experimental rate data for the material under investigation. The use of simple expressions such as equations (24) and (25) may be entirely adequate, depending upon activation energy for the decomposition process and order of reaction.

The aerodynamic heating input in the analysis consists of convective and radiative components treated separately. This distinction is necessary since the convective heating can be significantly reduced as a result of the injection of the ablation gases into the boundary layer, with generally no effect on radiant heating. Reduction in the convective heating rate can be approximated by the following expression (ref. 6):

$$\dot{q}_{block} \equiv \eta \dot{m}_g \left(H_T - H_w\right) \tag{27}$$

Therefore,

$$\dot{q}_{c,blow} = \dot{q}_{cw}\left(\frac{H_T - H_w}{H_T - H_{300}}\right) - \dot{q}_{block} \tag{28}$$

However, equation (28) is unsatisfactory for high blowing rates, since $\dot{q}_{block}$ can become greater than $\dot{q}_{cw}$. An experimental curve of blocking effectiveness $\psi = \frac{\dot{q}_{c,blow}}{\dot{q}_{cw}}$ as a function of the mass transfer parameter $\frac{\dot{m}_g H_T}{\dot{q}_{cw}}$ can be employed to determine the heating reduction at high blowing rates. Both methods have been employed in the STAB II analysis. Equation (28) is presently in use. However, no satisfactory method for accurately predicting the convective heat blockage has been determined.

Another source of heating is the combustion of the ablation products in the boundary layer. Reference 7 presents an analysis of the oxidation of a carbon surface and the resulting combustive heating. The heating due to combustion as derived in reference 7 is

$$\dot{q}_{comb} = \dot{m}_c \, \Delta H_c \tag{29}$$

where $\Delta H_c$ is the heat of combustion per unit weight of char.

The thermal properties of the ablation material are both temperature and state dependent (fully or partially charred). Figure 4 is an illustration of the variation of these properties with temperature and state. The thermal properties are assumed to vary as follows:

(1) Char zone $\left(T_i \geq T_{char}\right)$

$$k_c = f\ (temp)$$

$$c_{p_c} = f\ (temp)$$

$$\rho_c = constant$$

(2) Reaction zone $\left(T_{abl} \leq T_i < T_{char}\right)$

$$\rho = f\ (temp) = \rho_v + \left(\rho_v - \rho_c\right)\left(\frac{T_i - T_{abl}}{T_{abl} - T_{char}}\right)$$

$$k = f(\rho) = k_c + \left(k_v - k_c\right)\left(\frac{\rho_i - \rho_c}{\rho_v - \rho_c}\right)$$

$$c_p = f(\rho) = c_{p_c} + \left(c_{p_v} - c_{p_c}\right)\left(\frac{\rho_i - \rho_c}{\rho_v - \rho_c}\right)$$

(3) Virgin zone $\left(T_i < T_{abl}\right)$

$$\rho_v = \text{constant}$$

$$k_v = f\ (\text{temp})$$

$$c_{p_v} = f\ (\text{temp})$$

The calculation of char removal, due to chemical, thermal, or mechanical mechanism or a combination of these mechanisms, has been examined by a multitude of investigators and numerous correlations exist, depending on the specific material involved.

To provide a maximum degree of flexibility for analyzing both ground and flight test data and synthesizing trajectories, the following provisions for char removal (surface movement) are provided:

(1) Removal of char as a function of surface temperature.

(2) Removal of char at a rate which is a function of time.

As the char is removed, the surface moves with respect to a coordinate fixed in the material. The distance between the initial surface location and the char surface is

$$S = \int_0^\theta \dot{S}\ d\theta$$

## ANALYSIS VERIFICATION

As discussed in the previous sections, approximations and assumptions were made in the analytical model to afford a quick and accurate solution in predicting the thermal response of a charring heat shield. These simplifying assumptions and approximations are expected to introduce only minor errors; however, the validity of the analyses and resultant accuracy can be judged only by a comparison with exact theoretical solutions and experimental data. Three examples have been selected, and a comparison of the STAB II results with the theoretical and test data is discussed in the following paragraphs.

An elementary transient heating example was chosen to demonstrate the accuracy and numerical stability of the STAB II program. A steel slab 6 inches thick was selected and assumed to be at uniform initial temperature of $460^\circ$ R ($0^\circ$ F). The thermal properties were considered constant. The

front surface was subjected to a heating rate of 72 $Btu/ft^2$-sec, and an adiabatic back surface was assumed. Figure 5 shows a comparison of the STAB II calculated in-depth temperatures as a function of time with the exact solution taken from reference 8.

To demonstrate the STAB II solution with a moving boundary, a slab with constant properties, uniform initial temperature, front surface moving with a constant velocity, and constant surface temperature was chosen. The exact solution for a semi-infinite slab with these boundary and initial conditions is presented in reference 9. Figure 6 presents a comparison of the STAB II temperature response with the exact solutions. As can be seen from this figure, the two solutions are not in agreement for approximately the first 50 to 60 seconds of the transient. This disagreement is the result of the quasi-steady state assumption made in the exact solution analysis.

$$\left[\left(\frac{\partial T}{\partial \theta}\right)_{\xi=0} = 0; \quad k\left(\frac{\partial T}{\partial X}\right)_{X=0} = \dot{S}\rho c_p \, \Delta T\right]$$

A calculation was made to estimate the induction time (time at which $\frac{\partial T}{\partial \theta} = 0$ is a good assumption) and found to be approximately 60 seconds, which is in agreement with the STAB II results.

Finally, to verify the fully charring ablation model, an example of a typical charring material was chosen. (See the sample problem in appendix A.) The charring ablation material is initially 1.6 inches thick with an adiabatic back surface and a constant heat flux of 95 $Btu/ft^2$-sec applied to the front surface. The surface is assumed to recede at a constant velocity of $3.05 \times 10^{-3}$ in./sec. Figure 7 presents a comparison of the in-depth temperatures with actual test results obtained in an arc tunnel. The results are in good agreement, with the largest deviations between calculated and measured values occurring for the thermocouple located at a depth of 1.0 inch. The disagreement could be attributed to several possible errors: thermal property values, incorrect location of thermocouples, et cetera. The effect of varying the thermal properties (thermal conductivity, specific heat, et cetera) is presently being investigated.

Tables I and II present the input and output data used for this example. Figures 8, 9, and 10 are the resulting plot routine output.

The comparisons between the computer results and the exact solutions and test results are considered satisfactory.

## CONCLUDING REMARKS

An analysis and a computer program for predicting the transient thermal response of a charring ablation thermal protection system has been described. The numerical formulation of the equations is such that an implicit solution is obtained. This method of solution affords both a rapid and accurate solution for both ablating and nonablating type problems.

Provision is made in the program for a number of surface boundary conditions. These provisions allow efficient use of the program for analyzing both ground and flight test data and trajectory synthesis.

The computer program has been checked out with both exact solutions and actual ablation test data. The numerical results are in good agreement with the exact solutions and test data. However, the analysis depends upon using good property values, and some effort must be expended in obtaining the best possible thermal properties.

Manned Spacecraft Center
National Aeronautics and Space Administration
Houston, Texas, November 1, 1965

## REFERENCES


1. Israel, Martin H.; and Nardo, S. V.: An Annotated Bibliography on Ablation and Related Topics. PIBAL rep. no. 686, Polytechnic Institute of Brooklyn, May 1964.

2. Hurwicz, Henryk: Aerothermochemistry Studies in Ablation. Fifth AGARD Colloquium on High-Temperature Phenomena (Braunschweig, Germany, April 9-13, 1962, Pergamon Press, New York, 1963.

3. Liebmann, G.: A New Electrical Analogue Method for the Solution of Transient Heat Conduction Problems. Transactions of the ASME, vol. 78, no. 3, 1956, p. 655.

4. Forsythe, George E.; and Wasow, Wolfgang R.: Finite-Difference Methods for Partial Differential Equations. John Wiley and Sons, Inc., New York, 1960.

5. Angelone, J., et al: Development of a Reinforced Carbonaceous and Ablative Composite for Entry Heat Protection of Manned Spacecraft. Tech. Rep. 330.17, Astronautics Div., Chance-Vought Corp., July 1963.

6. Roberts, Leonard: Mass Transfer Cooling Near the Stagnation Point. NASA TR R-8 (Supersedes NACA TN 4391), 1959.

7. Dow, Marvin M.; and Swann, Robert T.: Determination of Effects of Oxidation on Performance of Charring Ablators. NASA TR R-196, 1964.

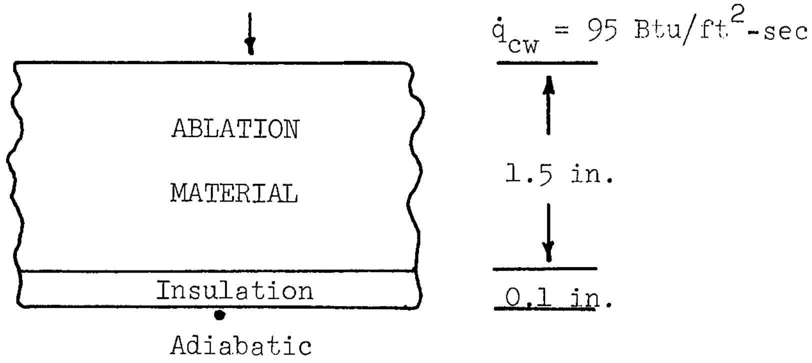
8. Carslaw, H. S.; and Jaeger, J. C.: Conduction of Heat in Solids. Clarendon Press, Oxford, 1959.

9. Schneider, Paul J.: Conduction Heat Transfer. Addison-Wesley Publishing Co., Inc., c. 1955.

## APPENDIX A

### SAMPLE PROBLEM

The following sample problem is shown to indicate the form of the data input and the program output. A typical charring material subjected to a constant heating rate as experienced in an arc tunnel is presented. The following is a sketch of the model:




The various material properties and dimensions are shown in the program output of Table II. The insulation is assumed to be ablation material for this problem. The problem coding sheet and subsequent data card listing are shown in Table I. The initial temperature of the structure was assumed uniform and equal to 530° R (70° F). Figures 8, 9, and 10 are the output data obtained from the plot routines.

APPENDIX B

PROGRAM USAGE INSTRUCTIONS

IBM 7094/40 program F021, standard ablation program, designated STAB II, is designed to evaluate the transient thermal performance of a charring ablation heat protection system. The program considers one ablating material and up to 12 different materials in the supporting backup structure. A maximum of 50 nodes may be considered in the ablation material, and a maximum of 10 nodes per material is allowed for each backup structure material. Air gaps can be considered between successive materials in the backup, thus allowing for both radiative and/or convective heat transfer between materials. The heat loss to the cabin environment from the backup structure can be accomplished by both radiation and/or convection, or an adiabatic backface surface may be prescribed.

Unless otherwise specified, the input problem data are in "floating point" form (E12.8 format) and must end in columns 12, 24, 36, 48, 60, and 72. It is suggested that each floating point number have a sign, a two-digit exponent, and a decimal point. For example, the number 145.23 can be written as +1.4523 +02, +145.23 +00, or +.14523 +03.

Input Nomenclature

The nomenclature used in the problem data input is as follows:

NCASE number of problems to be run successively

HEAD any 72 alphabetical and/or numerical characters

TITLE control card for reading in new input for successive problems

1. blank card – new data will be read in

2. Six asterisks in columns 1 to 6. Skip to next read statement

TLIM time limit of problem, sec

TINT starting time of problem, sec

NPTT number of points in time-step table (the minimum value of NPTT is 2)

NPLØT output plot control

=1 plot routine will be used

=0 plot routine will be ignored

| | |
|---|---|
| TTABLE | time in time-step table, sec |
| DELTT | time step to be used for each calculation - starting at time TTABLE, sec |
| IPRC | variable print frequency in TTABLE table; that is, if DELTT = 1.0 and IPRC = 10, the output will be printed at 10-second intervals |
| FCØNV | factor to correct convective heating rate for various body locations |
| FRAD | factor to correct radiative heating for various body locations |
| TABL | temperature at which ablation starts, $^{\circ}R$ |
| TCHAR | temperature at which ablation stops, $^{\circ}R$ |
| TREC | surface temperature, $^{\circ}R$, <u>or</u> time at which char removal is to start, sec |
| RHØV | density of virgin ablation material, $lb/ft^3$ |
| RHØC | density of mature char material, $lb/ft^3$ |
| FBLØW | blowing efficiency of ablation gases in reducing convective heating |
| EMV | emissivity of virgin ablation material |
| EMC | emissivity of charred ablation material |
| H300 | enthalpy of air at $300^{\circ}$ K, 129.06 Btu/lbm |
| VL | initial thickness of virgin ablation material, in. |
| HV | heat of degradation of virgin material, Btu/lbm |
| VPT | test to determine if the reaction zone and char zone thermal properties are irreversible with temperature |
| =0 | properties are irreversible and equal to the value at the maximum individual node temperature (this is the recommended value for VPT) |
| =1 | properties are reversible |
| FV | view factor for external environment |
| TV | sink temperature of external environment, $^{\circ}R$ |

| | |
|---|---|
| CHARK | thermal conductivity of material at TCHAR, Btu/ft-hr-$^{\circ}$R |
| CHARC | specific heat of material at TCHAR, Btu/lbm-$^{\circ}$R |
| ABLK | thermal conductivity of material at TABL, Btu/ft-hr-$^{\circ}$R |
| ABLC | specific heat of material at TABL, Btu/lbm-$^{\circ}$R |
| NP | number of node points in ablation material |
| NKC | number of points in char thermal conductivity – temperature table |
| NCPC | number of points in char specific heat – temperature table |
| NKV | number of points in virgin thermal conductivity – temperature table |
| NCPV | number of points in virgin specific heat – temperature table |
| NREC | number of points in surface recession – temperature <u>or</u> time table |
| TKC | temperature values in char thermal conductivity – temperature table, $^{\circ}$R |
| XKC | thermal conductivity values in char thermal conductivity – temperature table, Btu/ft-hr-$^{\circ}$R |
| TCPC | temperature values in char specific heat – temperature table, $^{\circ}$R |
| CPC | specific heat values in char specific heat – temperature table, Btu/lbm-$^{\circ}$R |
| TKV | temperature values in virgin thermal conductivity – temperature table, $^{\circ}$R |
| XKV | thermal conductivity values in virgin thermal conductivity – temperature table, Btu/ft-hr-$^{\circ}$R |
| TCPV | temperature values in virgin specific heat – temperature table, $^{\circ}$R |
| CPV | specific heat values in virgin specific heat temperature table, Btu/lbm-$^{\circ}$R |
| TS | temperature, $^{\circ}$R, or time, sec, values in the surface recession table |

| | |
|---|---|
| SR | surface recession values in the surface recession – temperature or time table, in./sec |
| NTRAPT | number of time points in the trajectory input table |
| TIME | the array of (NTRAPT) trajectory time values, sec |
| QCØN | the corresponding array of cold wall convective heating rates, Btu/$ft^2$-sec |
| QRAD | the corresponding array of radiative heating rates, Btu/$ft^2$-sec |
| VEL | the corresponding array of flight velocity, ft/sec |
| NMB | number of materials in backup structure |
| NPBS | total number of node points in backup structure |
| BL | total thickness of backup structure, in. |
| XNPM | number of nodes in <u>each individual</u> material in backup structure |
| NKPB | number of points in each individual backup structure material thermal conductivity – temperature table |
| NCPB | number of points in <u>each individual</u> backup structure material specific heat – temperature table |
| XIDNT | any 72 alphanumeric characters used to describe <u>each individual</u> material in the backup structure |
| TXK | temperature values in backup material thermal conductivity – temperature table, $^{o}R$ |
| XK | thermal conductivity values in backup material thermal conductivity – temperature table, Btu/ft–hr–$^{o}R$ |
| TCP | temperature values in backup material specific heat – temperature tables, $^{o}R$ |
| CPX | specific heat values in backup material specific heat – temperature tables, Btu/lbm-$^{o}R$ |
| RHØBX | density of individual materials in backup, lb/$ft^3$ |
| XBM | thickness of individual materials in backup, in. |
| EMFB | emissivity of front surface of each material in backup |

| | |
|---|---|
| EMBB | emissivity of back surface of each material in backup |
| H | film coefficient between adjacent materials in backup, $Btu/ft^2\text{-}hr\text{-}^{o}R$ |
| GAPX | width of gap between adjacent materials in backup, in. |
| FTEST, BTEST | tests to determine the mode of heat transfer between materials for the front and backface of each material respectively |
| =0 | conduction only between materials |
| =+1 | convective heat transfer only |
| =-1 | radiation only or radiation and convection heat transfer |
| TENV | temperature of interior cabin environment, $^{o}R$ |
| HENV | film coefficient to interior cabin environment, $Btu/ft^2\text{-}hr\text{-}^{o}R$ |
| FENV | view factor and emissivity product for radiative heat transfer to cabin interior |
| QLØSS | boundary condition between last node of the backup structure and cabin environment |
| =0 | adiabatic surfaces |
| =+1 | radiation and/or convective loss |
| TEST2 | determines the proper heat shield initial temperature distribution |
| =0 | constant, uniform initial temperature distribution |
| =-1 | arbitrary initial temperature distribution |
| =+1 | linear temperature distribution |
| TEMPI | temperature to be used when constant temperature distribution option is used, $^{o}R$ |
| TXØ | initial temperature at front surface of heat shield to be used in computing initial linear temperature gradient, $^{o}R$ |
| TEMDI | arbitrary temperature distribution values, to be used only if TEST2 is negative, $^{o}R$ |

NHP number of points in enthalpy – temperature curve fit

HX enthalpy values in enthalpy – temperature table, Btu/lbm

TW corresponding temperature values in enthalpy – temperature table, $^{\circ}R$

## Input Data Card Preparation

The input data are given in the following order. Each number in the following listing refers to a separate record and must begin on a new data card. The input data have been grouped, where possible, into various sections dealing with a particular part of the input, that is, ablation material properties, trajectory data, backup structure, et cetera. This grouping permits the use of a minimum number of input cards for running successive problems. The title card as described in the input nomenclature controls the input for successive problems.

1. The first data card contains the value of NCASE. NCASE is an integer (I5 format) and must end in column 5. This card tells how many problems are to be run and is entered only <u>once</u> at the start of the data deck.

2. Columns 1 to 72 of the second data card contain any title or identification information desired; any alphanumeric character may be used. This card is printed at the top of the first page of the output. This card <u>must</u> be included in all successive problems to be run.

(a) Problem time section

3. TITLE card – if blank, cards 4 and 5 must be submitted. If six asterisks are punched in columns 1 to 6, skip to record number 6.

4. This record contains, in the following order, TLIM, TINT, NPTT, and NPLØT. TLIM and TINT are entered as floating-point numbers and must end in columns 12 and 24. NPTT and NPLØT are integers entered with an I5 format and must end in column 30 and 35.

5. Start entering the values of TTABLE, DELTT, IPRC. TTABLE and DELTT are floating-point numbers and must end in columns 12 and 24. IPRC is entered as integer with an I5 format and must end in column 30. Use as many cards as required to enter NPTT values.

(b) Heating rate factors section

6. TITLE card - if blank, card 7 must be submitted. If six asterisks are punched in columns 1 to 6, skip to record number 8.

7. Enter the FCØNV and FRAD. These numbers are entered as floating-point numbers and must end in columns 12 and 24.

(c) Ablation material section

8. TITLE card – if blank, cards 9 to 18 must be submitted. If six asterisks are punched in columns 1 to 6, skip to record number 19.

9. HEADNG card – any alphanumeric characters in columns 1 to 72. Records 9 to 18 contain input data for the ablation material.

10. Enter TABL, TCHAR, TREC, RHØV, RHØC, and FBLØW. These numbers are entered as floating-point numbers (6E12.8 format) and must end in columns 12, 24, 36, 48, 60, and 72.

11. Enter EMV, EMC, H300, VL, HV, and VPT. Use the same format as card 10.

12. Enter FV, TV, CHARK, CHARC, ABLK, and ABLC. Use the same format as card 10.

13. This card contains, in the following order, NP, NKC, NCPC, NKV, NCPV, and NREC. These numbers are fixed-point integers and must end in columns 5, 10, 15, 20, 25, and 30. An I5 format is used to read in these numbers.

14. Start entering the curve of TKC versus XKC, with the values of TKC ending in columns 12, 36, and 60. The corresponding values of XKC must end in columns 24, 48, and 72; for example, three TKC-XKC points are contained on one card. The numbers are entered as floating-point numbers. Use as many cards as required to enter NKC points on the curve.

15. Start entering the curve of TCPC versus CPC with the values of TCPC, ending in columns 12, 36, and 60. The corresponding values of CPC must end in columns 24, 48, and 72; for example, three TCPC-CPC points are contained on one card. The numbers are entered as floating-point numbers. Use as many cards as required to enter the NCPC points on the curve.

16. Start entering the curve of TKV versus XKV with the values of TKV ending in columns 12, 36, and 60. The corresponding values of XKV must end in columns 24, 48, and 72; for example, three TKV-XKV points are contained on one card. The numbers are entered as floating point. Use as many cards as required to enter the NKV points on the curve.

17. Start entering the curve of TCPV versus CPV with the values of TCPV, ending in columns 12, 36, and 60. The corresponding values of CPV must end in columns 24, 48, and 72; for example, three TCPV-CPV points are contained on one card. The numbers are entered as floating point. Use as many cards as required to enter NCPV points on the curve.

18. Start entering the curve of TS versus SR with the values of TX, ending in columns 12, 36, and 60. The corresponding values of SR must end in columns

24, 48, and 72; for example, three TS-SR points are contained on one card. The numbers are entered as floating point. Use as many cards as required to enter NREC points on the curve.

(d) Trajectory data section

19. TITLE card - if blank, cards 20 to 22 must be submitted; if six asterisks are punched in columns 1 to 6, skip to record number 23.

20. HEADNG card - any alphanumeric characters in columns 1 to 72. Records 21 and 22 contain trajectory input data.

21. Enter NTRAPT. This number is an integer and must end in column 5. An I5 format is used to read in this number.

22. Start entering the trajectory data in the following order: TIME, QCØN, QRAD, VEL. These values are entered as floating-point numbers and must end in columns 12, 24, 36, and 48. There are four trajectory data points on one card. Use as many cards as required to enter NTRAPT points in the trajectory.

(e) Backup structure section

23. TITLE card - if blank, cards 24 to 31 must be submitted; if six asterisks are punched in columns 1 to 6, skip to record number 32.

24. Enter NMB, NPBS, and BL. These three values must end in columns 5, 10, and 24. NMB and NPBS are integers and are read in under an I5 format. BL is a floating-point number.

25. Enter the values of XNPM. XNPM is in floating-point form and must end in columns 12, 24, 36, 48, 60, and 72. Use as many cards as required to enter NMB points.

26. Enter the values of NKPB and NCPB. These numbers are integers and NKPB must end in columns 5, 15, 25, 35, and 45; and the corresponding values of NCPB must end in columns 10, 20, 30, 40, and 50. An I5 format is used to read these values. Five NKPB-NCPB values are contained on one card. Use as many cards as are required to enter NMB points.

27. XIDNT card - any alphanumeric characters in columns 1 to 72. This card contains a description of each backup material.

28. Start entering the curve of TXK versus XK with the values of TXK, ending in columns 12, 36, and 60. The corresponding values of XK must end in columns 24, 48, and 72; for example, three TXK-XK points are contained on one card. The numbers are entered as floating point. Use as many cards as required to enter NKPB points on the curve.

29. Start entering the curve of TCP versus CPX with the values of TCP, ending in columns 12, 36, and 60. The corresponding values of CPX must end in columns 24, 48, and 72; for example, three TCP–CPX points are contained on one card. The numbers are entered as floating point. Use as many cards as required to enter NCPB points on the curve. Repeat records 27, 28, and 29 until the properties for NMB materials have been entered. The maximum number for NMB is 12.

30. Start entering the following values in order: RHØBX, XBM, EMFB, and EMBB. These values are entered as floating-point numbers (6E12.8 format) and must end in columns 12, 24, 36, 48, 60, and 72. Use as many cards as required to enter NMB points.

31. Start entering the following values in order: H, GAPX, FTEST, and BTEST. These values are entered as floating–point numbers (6E12.8 format) and must end in columns 12, 24, 36, 48, 60, and 72. Use as many cards as required to enter NMB points.

(f) Interior environment section

32. TITLE card – if blank, cards 33 and 34 must be submitted; if six asterisks are punched in columns 1 to 6, skip to record number 35.

33. HEADNG card – any alphanumeric characters in columns 1 to 72. Record 35 contains properties of environment.

34. Enter the following: TENV, HENV, FENV, and QLØSS. The values are entered as floating–point numbers and must end in columns 12, 24, 36, and 48.

(g) Initial temperature section

35. TITLE card – if blank, records 36 and 37 must be submitted; if six asterisks are punched in columns 1 to 6, skip to record 39.

36. HEADNG card – any alphanumeric characters in columns 1 to 72. Records 37 and 38 contain initial temperature distribution input.

37. Enter TEST2, TEMPI, and TXØ. These values are entered as floating–point numbers and must end in columns 12, 24, and 36.

NOTE: If TEST2 is a negative number, record 38 must be submitted; otherwise, skip to record 39.

38. Enter the arbitrary temperature distribution values, TEMDI. These values are entered as floating points with a 6E12.8 format. Use as many cards as required to enter NP plus NPBS node points.

(h) Enthalpy - temperature section

39. TITLE card - if blank, records 40 and 41 must be submitted; if six asterisks are punched in columns 1 to 6, this is the last data card in the problem input.

40. Enter NHP. This value is an integer and must end in column 5. An I5 format is used to read in this number.

41. Start entering the curve of HX versus TW with the value of HX ending in columns 12, 36, and 60. The corresponding values of TW must end in columns 24, 48, and 72; for example, three HX-TW points are contained on one card. The numbers are entered as floating points. Use as many cards as required to enter NHP points on the curve. Record 41 consists of the last data cards required as input for a problem.

As many successive problems as desired may be run at one time by proper input preparation. STAB II has been designed to save all input information until it is changed by new input data. Therefore, the use of the TITLE control card is very important when running more than one problem and using the input data of previous problems. As shown, each input section starts with a TITLE control card for determining whether new input data are to be used. If <u>any data</u> are changed within a section, then <u>all data</u> cards required for that section must be submitted.

STAB II can also be used for solving one-dimensional transient heat-conduction problems of nonablating materials. The following input parameters must be adhered to:

1. TABL must be greater than the maximum temperature expected during the calculation. Also, TABL $>$ TCHAR $>$ TREC.

2. The ablation material must be considered to be the first material in the structure for calculation purposes.

3. The virgin and char properties must be inputed as described above but can have the same values; that is, XKV = XKC, CPC = CPV, RHØV = RHØC, et cetera.

The following dimensional statements and program limitations should not be violated when preparing the input described above for ablating and nonablating structure:

1. All property tables can have a maximum of 20 points (i.e., a temperature and specific heat value constitute one point).

2. The surface recession table can have a maximum of 50 points (TS and SR constitute one point).

3. The trajectory table can have a maximum of 300 points (TIME, QCØN, QRAD, and VEL constitute one point).

4. The ablation material can be broken into a maximum of 50 nodes. The backup structure can consist of up to 12 different materials with a maximum of 10 nodes per material.

5. A minimum of three nodes per material (ablation or backup) must be specified.

6. A minimum of two materials must be specified (ablation material and one backup structure material).

7. Pure conduction only is allowed between the ablation material and the first material in the backup.

8. If any data input is changed in the Ablation Material Section on successive problems, the Ablation Material Section data cards plus the Initial Temperature Section data cards must be submitted.

## Program Output Information

The computed results are available in two forms of output: tabular and plot outputs. The tabular output presents the computed results in block type form for each computation step as controlled by the print count control number. As discussed in the preparation of input data, both the computational time step and print control can be varied throughout the running of a problem. Therefore, excessive printed output is avoided, and there is a considerable savings in actual machine computation time. The plot outputs are printed and plotted only when the entire set of problems to be run are completed.

Tabular output. - The program prints a listing of the data input parameters for identification of the problem and ease in identifying any input mistakes. For stacked problems, the program prints only that input information that is changed from the previous problem. The following calculated problem output is printed:

1. Time, sec

2. Cold wall convective heating rate without blowing, Btu/ft$^2$-sec

3. Radiative heating rate, Btu/ft$^2$-sec

4. Velocity, ft/sec

5. Gas ablation rate, lbm/ft$^2$-hr

6. Char ablation rate, lbm/ft$^2$-hr

7. Total ablation rate, lbm/ft$^2$-hr

8. Surface recession depth from original surface, in.

9. Hot wall convective heating rate without blowing, $Btu/ft^2$-sec

10. Temperature distribution in ablation material, $^{\circ}R$

11. Temperature distribution in backup structure, $^{\circ}R$

The temperatures printed for the ablation material are for fixed distances from the original surface. These distances are calculated from the initial ablation material thickness and number of nodes in ablation material. For example

let

$$VL = 1.0 \text{ in.}$$

$$NP = 11$$

then

$$\Delta X = \frac{VL}{NP - 1} = 0.1$$

The temperatures will be printed for X distances of 0, 0.1, 0.2, 0.3, et cetera, from the original surface until the surface has receded beyond these fixed distances at which time the node no longer exists and is dropped from the printout. This is illustrated in the following way: let surface recession = 0.26 inch. The first temperature printed then is the surface temperature of the material, located 0.26 inch from the original material surface. The following printed ablation material temperatures are for X distances of 0.3, 0.4, 0.5, ..., 1.0 inch.

The format for the temperature distribution printout is E16.5 with six temperatures printed per line.

<u>Plot output</u>. – The plot output gives the following ablative material performance parameters as a function of time:

1. Surface depth, in.

2. Bondline temperature between ablator and backup structure, $^{\circ}R$

3. Two selected isotherm depths

These values are also printed in tabular form for ease in checking and replotting of the results. The plotted curves contain all maximum and minimum values of the parameters.

## APPENDIX C

## PROGRAM IN FORTRAN STATEMENTS

```
$IBFTC MAIN
C
C      STRUCTURES AND MECHANICS DIVISION
C      THERMO-STRUCTURES BRANCH
C      THERMAL PROTECTION SYSTEMS SECTION
C
C      THIS PROGRAM DETERMINES THE PERFORMANCE OF A CHARRING ABLATOR
C
C      ANALYSIS AND PROGRAM DEVELOPED BY DONALD M. CURRY  *  ES32
C
      DIMENSION ESAVE1(3),ESAVE2(3),ESAVE3(3)
      DIMENSION TITLE(12),HEADNG(12),XIDNT(12,12),TKC(20),XKC(20),
     1CPC(20),TKV(20),XKV(20),TCPV(20),CPV(20),TIME(300),QCON(300),
     2QRAD(300),VEL(300),XNPM(12),NKPB(12),NCPB(12),TXK(20,12),XK(20,12)
     3,TCP(20,12),CPX(20,12),RHOBX(12),XBM(12),FMFB(12),EMBB(12),HXX(12)
     4,GAPX(12),FTEST(12),BTEST(12),TEMDI(200),TX1(200),TX2(200),
     5TX2T(10,12),TUL1(200),TUL2(200),HX(50),TW(50),IR(50),IR1(50),
     6IR2(50),TUL(50),IEM(50),TY(200),A(200),B(200),C(200),D(200),
     7R(50),RHO(50),CP(50),DXB(12),XKB(10,12),CPB(10,12),XMDG(50),
     8YK(50),AB(10,12),BB(10,12),CB(10,12),DB(10,12),SB(10,12),
     9RB1(10,12),RB2(10,12),H(12),S(50),NPM(12)
      DIMENSION TTUL(50),RHOY1(50),RHOY2(50),DRHO(50),TCPC(20)
      DIMENSION TIMEP(300),PRES(300),XC(50),TX2C(50),XV(50),XDV(50)
      DIMENSION TS(50),SR(50)
      DIMENSION TTABLE(20),DELTT(20),IPRC(20)
      DIMENSION ASAVE1(3),ASAVE2(3),ASAVE3(3),BSAVE1(3),BSAVE2(3),
     1BSAVE3(3),CSAVE1(3),CSAVE2(3),CSAVE3(3),HEAD(12),
     1DSAVE1(3),DSAVE2(3),DSAVE3(3)
      DIMENSION XRA(30),YA(30)
C
      COMMON TKC,XKC,TCPC,CPC,TKV,XKV,TCPV,CPV,XNPM,RHOBX,XBM,FMBB,
     1FMFB,NKPB,NCPB,TXK,XK,TCP,CPX,NPM,GAPX,FTEST,BTEST,TEMDI,TX1,
     2TX2,TX2T,TUL,TUL1,TUL2,IR,IR1,IR2,A,B,C,D,S,R,AB,BB,CB,DB,SB,
     3RB1,RB2,TY,RHOY1,RHOY2,XMDG,RHO,CP,YK,XKB,CPB,DXB,DT,XLOST,
     4TABL,TCHAR,TREC,RHOV,RHOC,FBLOW,FMV,EMC,H300,NKC,NCPC,NKV,NCPV,
     5NP,NMB,NPBS,NPF,TEST2,TEMPI,TX0,TENV,HENV,FENV,QLOSS,TLIM,TINT
      COMMON I1,I2,I3,I4,I5,I6,QIN,INT,DX,XMT,TL,VL,BL,DMP,ERR1,ERR2,
     1ERR3,ERR4,HV,VPT,CHARK,CHARC,ABLK,ABLC,XMDC,H
C
 3000 FORMAT(12A6)
 3001 FORMAT(1X,12A6)
 3002 FORMAT(6E12.8)
 3003 FORMAT(6I5)
 3004 FORMAT(1I5)
 3005 FORMAT(2I5)
 3007 FORMAT(2I5,1E14.8)
 3008 FORMAT(///1X,12A6)
 3009 FORMAT(1H1,1X,12A6)
 3010 FORMAT(4E12.8)
 3011 FORMAT(2E12.8,I6,I5,F13.8,E12.8)
 3012 FORMAT(2E12.8,I6)
      DATA PRVOUS/0545454545454/
      REWIND 11
      STOP=9999.
      READ(5,3003)NCASE
      LPLOT=0
      JCNT=0
```

```
   50 NK=1
      I1=2
      I2=2
      I3=2
      I4=2
      I5=2
      I6=2
      I17=2
      INT=1
      XLOST=0.0
      XMT=0.0
      XMDT=0.0
      ERR1=0.0
      ERR2=0.0
      ERR3=0.0
      ERR4=0.0
      ICT=0
      ICONT=0
      XMDC=0.0
      NKP=1
      XLSTV=0.0
      NRS=2
      ERR5=0.0
      IPCT=0
      ICTP=0
      IPLOT=1
      NXA=1
      NXB=1
      NXC=1
      NXD=1
      SAVY3=-100.
      SAVY4X=-100.
      SX0=0.0
      SDOT=0.0
C
C     GENERAL TITLE OF PROBLEM
  100 READ(5,3000) (HEAD(K),K=1,12)
      WRITE(6,3009) (HEAD(K),K=1,12)
      LPLOT=LPLOT+1
      WRITE (11)(HEAD(I),I=1,12)
      WRITE(6,110)
  110 FORMAT(//1X,11HINPUT DATA.//)
      READ(5,3000) (TITLE(L),L=1,12)
      IF(TITLE(1).EQ.PRVOUS) GO TO 150
      READ(5,3011)TLIM,TINT,NPTT,NPLOT,DMP,TDMP
      READ(5,3012) (TTABLE(I),DELTT(I),IPRC(I),I=1,NPTT)
      T=TINT
      DTS=DELTT(1)
      DT=DELTT(1)/3600.0
      WRITE(6,120) TLIM,TINT,NPTT
  120 FORMAT(1H0,11HTIME LIMIT=,1PE10.4,4X,13HINITIAL TIME=,1PE10.4,4X,5
     1HNPTT=,I4)
      WRITE(6,122)
  122 FORMAT(//8X,4HTIME,10X,9HTIME STEP,6X,13HPRINT CONTROL)
      WRITE(6,124) (TTABLE(I),DELTT(I),IPRC(I),I=1,NPTT)
  124 FORMAT(5X,1PE10.4,6X,1PE10.4,9X,I4)
C
```

```
C      LOCATION FACTORS FOR CONVFCTIVE AND RADIATIVE HEATING
  150 READ(5,3000) (TITLE(L),L=1,12)
      IF(TITLE(1).EQ.PRVOUS) GO TO 200
      READ(5,3002) FCONV,FRAD
      WRITE(6,155) FCONV,FRAD
  155 FORMAT(1H0,6HFCONV=,1PE12.5,4X5HFRAD=,1PE12.5/)
C
C      PROPERTIES OF ABLATION MATERIAL
  200 READ(5,3000) (TITLE(L),L=1,12)
      IF(TITLE(1).EQ.PRVOUS) GO TO 300
      READ(5,3000) (HEADNG(K),K=1,12)
      READ(5,3002) TABL,TCHAR,TREC,RHOV,RHOC,FBLOW,FMV,EMC,H300,VL,HV,
     1VPT,FV,TV,CHARK,CHARC,ABLK,ABLC
      REA (5,3003) NP,NKC,NCPC,NKV,NCPV,NREC
      READ(5,3002) (TKC(K),XKC(K),K=1,NKC)
      READ(5,3002) (TCPC(M),CPC(M),M=1,NCPC)
      READ(5,3002) (TKV(L),XKV(L),L=1,NKV)
      READ(5,3002) (TCPV(N),CPV(N),N=1,NCPV)
      READ(5,3002) (TS(I),SR(I),I=1,NREC)
      WRITE(6,3008) (HEADNG(K),K=1,12)
      WRITE(6,210) TABL,TCHAR,TREC,RHOV,RHOC,FBLOW,FMV,EMC,H300,VL,HV,
     1VPT,FV,TV,CHARK,CHARC,ABLK,ABLC
  210 FORMAT(1H0,5HTABL=,1PE12.5,3X,6HTCHAR=,1PE12.5,3X,5HTREC=,1PE12.5,
     13X,5HRHOV=,1PE12.5,3X,5HRHOC=,1PE12.5,21X/1X,6HFBLOW=,1PE12.5,4X,4
     2HFMV=,1PE12.5,4X,4HEMC=,1PE12.5,3X,5HH300=,1PE12.5,5X,3HVL=,1PE12.
     35/4X,3HHV=,1PE12.5,4X,4HVPT=,1PE12.5,5X,3HFV=,1PE12.5,5X,3HTV=,1PE
     112.5,2X,6HCHARK=,1PE12.5/1X,6HCHARC=,1PE12.5,3X,5HABLK=,1PE12.5,3X
     2,5HABLC=,1PE12.5/)
      VLI=VL
      VL=VL/12.0
      VLV=VL
      WRITE(6,220) NP,NKC,NCPC,NKV,NCPV,NREC
  220 FORMAT(2X,3HNP=,1I4,4X,4HNKC=,1I4,4X,5HNCPC=,1I4,4X,4HNKV=,1I4,4X,
     15HNCPV=,1I4,4X,5HNREC=,1I4)
      WRITE(6,221)
  221 FORMAT(/32X,15HVIRGIN MATERIAL/20X,7HTHERMAL,38X,8HSPECIFIC/3X,11H
     1TEMPERATURE,4X,12HCONDUCTIVITY,19X,11HTEMPERATURE,7X,4HHEAT)
      KLLL=MIN0(NKV,NCPV)
      WRITE(6,222) (TKV(L),XKV(L),TCPV(L),CPV(L),L=1,KLLL)
  222 FORMAT(2X,1PE12.5,4X,1PE12.5,18X,1PE12.5 ,3X,1PE12.5)
      IF(NKV-NCPV) 223,227,225
  223 KLLLL=KLLL+1
      WRITE(6,224) (TCPV(L),CPV(L),L=KLLLL,NCPV)
  224 FORMAT(48X,1PE12.5,3X,1PE12.5)
      GO TO 227
  225 KLLLL=KLLL+1
      WRITE(6,226) (TKV(L),XKV(L),L=KLLLL,NKV)
  226 FORMAT(2X,1PE12.5,4X,1PE12.5)
  227 WRITE(6,228)
  228 FORMAT(//33X,14HCHAR  MATERIAL/20X,7HTHERMAL,38X,8HSPECIFIC/3X,11H
     1TEMPERATURE,4X,12HCONDUCTIVITY,19X,11HTEMPERATURE,7X,4HHEAT)
      KLLL=MIN0(NKC,NCPC)
      WRITE(6,222) (TKC(L),XKC(L),TCPC(L),CPC(L),L=1,KLLL)
      IF(NKC-NCPC) 230,235,232
  230 KLLLL=KLLL+1
      WRITE(6,224) (TCPC(L),CPC(L),L=KLLLL,NCPC)
      GO TO 235
```

```
  232 KLLLL=KLLL+1
      WRITE(6,226) (TKC(L),XKC(L),L=KLLLL,NKC)
  235 WRITE(6,240)
  240 FORMAT(//28X,23HSURFACE RECESSION TABLE//25X,11HTEMPERATURE,8X,11H
     1SR - IN/SEC)
      WRITE(6,245) (TS(I),SR(I),I=1,NREC)
  245 FORMAT(24X,1PE12.5,7X,1PE12.5)
C
C     PROPERTIES OF TRAJECTORY
  300 READ(5,3000) (TITLE(L),L=1,12)
      IF(TITLE(1).EQ.PRVOUS) GO TO 400
      READ(5,3000) (HEADNG(L),L=1,12)
      READ(5,3004) NTRAPT
      READ(5,3010) (TIME(K),QCON(K),QRAD(K),VEL(K),K=1,NTRAPT)
      WRITE(6,3008) (HEADNG(L),L=1,12)
      WRITE(6,310) NTRAPT
  310 FORMAT(1H0,27H NO. OF TRAJECTORY POINTS =,1I4)
      WRITE(6,320)
  320 FORMAT(//8X,4HTIME,8X,12HQ CONVECTIVE,4X,11HQ RADIATIVE,7X,8HVELOC
     1ITY)
      WRITE(6,330) (TIME(K),QCON(K),QRAD(K),VEL(K),K=1,NTRAPT)
  330 FORMAT(1P4E16.5)
C
C     PROPERTIES OF BACK-UP STRUCTURE
  400 READ(5,3000) (TITLE(L),L=1,12)
      IF(TITLE(1).EQ.PRVOUS) GO TO 500
      WRITE(6,410)
  410 FORMAT(//10X,31H PROPERTIES OF BACKUP STRUCTURE/)
      READ(5,3007) NMB,NPBS,BL
      READ(5,3002) (XNPM(K),K=1,NMB)
      READ(5,415) (NKPB(I),NCPB(I),I=1,NMB)
  415 FORMAT(10I5)
      DO 420 K=1,NMB
      NPM(K)=XNPM(K)+0.00000002
  420 CONTINUE
      WRITE(6,425) NMB,NPBS,BL
  425 FORMAT(/4X,35HNO. OF MATERIALS IN BACK-UP SHIELD=,1I4/4X,40HTOTAL
     1NUMBER OF NODES IN BACK-UP SHIELD=,1I4/4X,28HTHICKNESS OF BACK-UP
     2SHIELD=,1PE12.5//)
      BL=BL/12.0
      DO 440 I=1,NMB
      LK=NKPB(I)
      LCP=NCPB(I)
      READ(5,3000) ((XIDNT(K,I)),K=1,12)
      READ(5,3002) ((TXK(J,I),XK(J,I)),J=1,LK)
      READ(5,3002) ((TCP(J,I),CPX(J,I)),J=1,LCP)
      WRITE(6,432) (XIDNT(K,I),K=1,12)
  432 FORMAT(//12A6)
      WRITE(6,433)
  433 FORMAT(//20X,7HTHERMAL,38X,8HSPECIFIC/3X,11HTEMPERATURE,4X,12HCOND
     1UCTIVITY,19X,11HTEMPERATURE,7X,4HHEAT)
      KLLL=MIN0(LK,LCP)
      DO 434 N=1,KLLL
      WRITE(6,222) (TXK(N,I),XK(N,I),TCP(N,I),CPX(N,I))
  434 CONTINUE
      IF(LK-LCP) 435,440,437
  435 KLLLL=KLLL+1
```

```
      DO 436 N=KLLLL,LCP
      WRITE(6,224) (TCP(N,I),CPX(N,I))
  436 CONTINUE
      GO TO 440
  437 KLLLL=KLLL+1
      DO 438 N=KLLLL,LK
      WRITE(6,226) (TXK(N,I),XK(N,I))
  438 CONTINUE
  440 CONTINUE
      READ(5,3002) (RHOBX(L),XBM(L),EMFB(L),EMBB(L),L=1,NMB)
      READ(5,3002)   (H(J),GAPX(J),FTEST(J),BTEST(J),J=1,NMB)
      WRITE(6,450)
  450 FORMAT(///55X,10HEMISSIVITY/8X,8HMATERIAL,5X,7HDENSITY,7X,9HTHICKN
     1ESS,7X,5HFRONT,9X,4HBACK,7X,14HNODES/MATERIAL/)
      DO 460 LLJ=1,NMB
      WRITE(6,455) LLJ,RHOBX(LLJ),XBM(LLJ),EMFB(LLJ),EMBB(LLJ),XNPM(LLJ)
  455 FORMAT(11X,1I1,8X,1PE10.4,4X,1PE10.4,4X,1PE10.4,4X,1PE10.4,6X,1PE1
     10.4/)
  460 CONTINUE
      WRITE(6,465)
  465 FORMAT(//4X,60HADDITIONAL DATA FOR INDIVIDUAL MATERIALS IN BACKUP
     1STRUCTURE//11X,8HMATERIAL,5X,16HFILM COEFFICIENT,5X,13HGAP THICKNE
     2SS,8X,5HFTEST,13X,5HBTEST)
      DO 480 J=1,NMB
      WRITE(6,470) J,  H(J),GAPX(J),FTEST(J),BTEST(J)
  470 FORMAT(13X,1I3,12X,1PE10.4,9X,1PE10.4,7X,1PE11.4,7X,1PE11.4/)
  480 CONTINUE
C
C     PROPERTIES OF ENVIRONMENT
  500 READ(5,3000) (TITLE(L),L=1,12)
      IF(TITLE(1).EQ.PRVOUS) GO TO 600
      READ(5,3000) (HEADNG(L),L=1,12)
      READ(5,3002) TENV,HENV,FENV,QLOSS
      WRITE(6,3008) (HEADNG(L),L=1,12)
      WRITE(6,520) TENV,HENV,FENV,QLOSS
  520 FORMAT(/4X,12HTEMPERATURE=,1PE12.5,4X,17HFILM COEFFICIENT=,1PE12.5
     1,4X,12HVIEW FACTOR=,1PE12.5,4X,7HQ LOST=,1PE12.5)
C
C     INITIAL TEMPERATURE DISTRIBUTION
  600 READ(5,3000) (TITLE(L),L=1,12)
      IF(TITLE(1).EQ.PRVOUS) GO TO 700
      READ(5,3000) (HEADNG(L),L=1,12)
      NPF=NP+NPBS
      TL=VL+BL
      XNP=NP
      DX=VL/(XNP-1.0)
      DXX=DX
      READ(5,3002) TEST2,TEMPI,TX0
      IF(TEST2) 610,620,620
  610 READ(5,3002) (TEMPI(K),K=1,NPF)
      DO 615 K=1,NPF
      TX1(K)=TEMPI(K)
      TX2(K)=TX1(K)
      TUL1(K)=TX1(K)
      TUL2(K)=TX1(K)
  615 CONTINUE
      L=NP+1
```

```
      DO 619 I=1,NMB
      LN=NPM(I)
      DO 617 J=1,LN
      TX2T(J,I)=TEMPI(L)
      L=L+1
  617 CONTINUE
  619 CONTINUE
      GO TO 625
  620 CALL TEMPD
  625 WRITE(6,3008) (HEADNG(L),L=1,12)
      IF(TEST2) 630,635,640
  630 WRITE(6,632)
  632 FORMAT(4X,52HTEMPERATURE DISTRIBUTION IN HEAT SHIELD IS ARBRITARY/
     1)
      WRITE(6,633) (TEMPI(K),K=1,NPF)
  633 FORMAT(1P8E12.5)
      GO TO 645
  635 WRITE(6,637) TEMPI
  637 FORMAT(//4X,64HTEMPERATURE DISTRIBUTION IN HEAT SHIELD IS UNIFORM
     1AND EQUAL TO ,1PE10.4/)
      GO TO 645
  640 WRITE(6,641)
  641 FORMAT(4X,54HLINEAR TEMPERATURE DISTRIBUTION ASSUMED IN HEAT SHIEL
     1D/)
      WRITE(6,633) (TEMPI(L),L=1,NPF)
  645 IF(DMP) 700,700,646
  646 WRITE(6,647)
  647 FORMAT(//)
  648 WRITE(6,649) (TX1(L),TX2(L),L=1,NPF)
  649 FORMAT(2X,1PE12.5,4X,1PE12.5)
      WRITE(6,650)
  650 FORMAT(//)
C
C     ENTHALPY AS A FUNCTION OF TEMPERATURE
  700 READ(5,3000) (TITLE(L),L=1,12)
      IF(TITLE(1).EQ.PRVOUS) GO TO 725
      READ(5,3004) NHP
      READ(5,3002) (HX(K),TW(K),K=1,NHP)
  725 DO 728 I=1,NP
      TR(I)=0
      TR1(I)=0
      TR2(I)=0
      TFM(I)=0
      XMDG(I)=0.0
  728 CONTINUE
      WRITE(6,730)
  730 FORMAT(1H1,12HOUTPUT DATA,//)
      XC(1)=0.0
      DO 740 I=2,NP
      XC(I)=XC(I-1)+DX
  740 CONTINUE
  750 IF(T-TIME(NK)) 765,770,760
  760 NK=NK+1
      IF(NK-NTRAPT) 750,750,762
  762 WRITE(6,763) NK
  763 FORMAT(1H0,33H THE VALUE OF NK IS IN ERROR, NK=,1I4)
      GO TO 905
```

```
  765 IF(NK-2) 762,766,766
  766 QCONX=QCON(NK-1)+((QCON(NK)-QCON(NK-1))/(TIME(NK)-TIME(NK-1)))
     1*(T-TIME(NK-1))
      QCONX=FCONV*QCONX
      QRADX=QRAD(NK-1)+((QRAD(NK)-QRAD(NK-1))/(TIME(NK)-TIME(NK-1)))
     1*(T-TIME(NK-1))
      QRADX=FRAD*QRADX
      VELX=VEL(NK-1)+((VEL(NK)-VEL(NK-1))/(TIME(NK)-TIME(NK-1)))
     1*(T-TIME(NK-1))
      GO TO 775
  770 QCONX=FCONV*QCON(NK)
      QRADX=FRAD*QRAD(NK)
      VELX=VEL(NK)
C
C     COMPUTE HEAT BLOCKAGE AT FRONT SURFACE
  775 IF(I17-1) 778,778,776
  776 IF(I17-NHP) 777,777,778
  777 IF(TX2(INT)-TW(I17)) 782,788,780
  778 WRITE(6,779) TX2(INT)
  779 FORMAT(1H0,80H THE RANGE OF THE ENTHALPY-TEMPERATURE CURVE FIT WAS
     1EXCEEDED AT A TEMPERATURE OF,1E10.4)
      GO TO 905
  780 I17=I17+1
      GO TO 776
  782 IF(TX2(INT)-TW(I17-1)) 784,788,786
  784 I17=I17-1
      GO TO 775
  786 HW=HX(I17-1)+((HX(I17)-HX(I17-1))/(TW(I17)-TW(I17-1)))
     1*(TX2(INT)-TW(I17-1))
      GO TO 789
  788 HW=HX(I17)
  789 HTX=H300+((VELX**2)/50056.5)
      QBLOCK=(FBLOW*XMDG(INT)*(HTX-HW))/3600.0
C
C     COMPUTE HEAT IN DUE TO SURFACE COMBUSTION
      XMDO=XMDC
      CALL OXIDAT(XMDO,QOXID)
C
C     COMPUTE Q-HOT WALL
      IF(TDMP.EQ.0.) GO TO 4001
      IF(T.GE.TDMP) DMP=1.0
 4001 Z=(HTX-HW)/(HTX-H300)
      IF(Z-1.0) 790,792,793
  790 IF(Z) 791,791,793
  791 QHW=0.0
      GO TO 1790
  792 QHW=QCONX
      GO TO 1790
  793 QHW=Z*QCONX
 1790 ZZZ=(QHW-QBLOCK)/QHW
      IF(ZZZ-0.2) 1798,1798,1794
 1798 QBLOCK=0.8*QHW
C
C     NET HEAT INTO FRONT SURFACE
 1794 IF(IEM(INT)) 795,795,797
  795 IF(TX2(INT)-TCHAR) 796,796,797
  796 EMX=EMV
```

```
      GO TO 798
  797 IFM(INT)=1
      FMX=EMC
  798 QIN=QRADX+QHW+QOXID-QBLOCK-(4.8333E-13)*FMX*FV*((TX2(INT)**4)-
     1(TV**4))
      IF(DMP) 804,804,800
  800 WRITE(6,801)
  801 FORMAT(///)
      WRITE(6,802) QCONX,QRADX,VELX,HTX,HW,Z,QBLOCK,QHW,QOXID,QIN
  802 FORMAT(1X,6HQCONX=,1PE12.5,2X,6HQRADX=,1PE12.5,2X,5HVELX=,1PE12.5,
     12X,4HHTX=,1PE12.5,2X,3HHW=,1PE12.5/1X,2HZ=,1PE12.5,2X,7HQBLOCK=,1P
     2E12.5,2X,4HQHW=,1PE12.5,2X,6HQOXID=,1PE12.5,2X,4HQIN=,1PE12.5/)
  804 QIN=QIN*3600.0
C
C     CHECK FOR FRONT SURFACE RECESSION (CHAR LAYER REMOVAL)
      CALL RECESS(XMDC,XLOST,TREC,DT,RHOC,TS,SR,TX2(1),NREC,NRS,ERR5,SX0
     1,SDOT,DMP)
      IF(ERR5) 8050,8050,905
 8050 VLV=VLV-XLOST
      XLSTV=XLSTV+XLOST
      XLSTI=XLSTV*12.0
      DXV=VLV/(XNP-1.0)
      XV(1)=0.0
      DO 1780 I=2,NP
      XV(I)=XV(I-1)+DXV
 1780 CONTINUE
      DX=DXV
      IF(ERR4) 806,806,805
  805 GO TO 905
  806 CALL COEFF(NPFT,SDOT)
      IF(DMP) 8069,8069,8061
 8061 WRITE(6,8062)
 8062 FORMAT(/1X,23H COEFFICIENTS FOR SWUFT/)
      DO 8066 I=1,NPFT
      WRITE(6,8064)  A(I),B(I),C(I),D(I),I
 8064 FORMAT(1H0,5HA(I)=,1PE12.5,2X,5HB(I)=,1PE12.5,2X,5HC(I)=,1PE12.5,2
     1X,5HD(I)=,1PE12.5,2X,2HI=,I3)
 8066 CONTINUE
 8069 IF(ERR2) 807,807,805
  807 IF(ERR3) 810,810,808
  808 WRITE(6,809) IKK
  809 FORMAT(1H0,18H THE VALUE OF IKK=,1I4)
      GO TO 905
  810 CALL SWUFT(A,B,C,D,TY,NPFT,DMP)
  827 DO 828 I=1,NP
      TX1(I)=TX2(I)
      TX2(I)=TY(I)
  828 CONTINUE
      CALL DON2(XLOST,XV,TX2,NP,XC,TX2C,XDV,KKV,XLSTV,DXX)
  830 CALL ABLATE
      XMDT=XMDG(INT)+XMDC
      LT=NP+1
      DO 1815 I=1,NMB
      LLT=NPM(I)
      IF(I.EQ.1) GO TO 1812
      IF(GAPX(I-1).EQ.0.) GO TO 1812
      KKT=1
```

```
      GO TO 1813                                                        A4560
 1812 KKT=2                                                             A4570
 1813 DO 1815 J=KKT,LLT                                                 A4580
      TX2T(J,I)=TY(LT)                                                  A4590
      LT=LT+1                                                           A4600
 1815 CONTINUE                                                          A4610
      DO 1819 I=1,NMB                                                   A4620
      IF(I.EQ.1) GO TO 1816                                             A4630
      IF(GAPX(I-1).EQ.0.) GO TO 1817                                    A4640
      GO TO 1819                                                        A4650
 1816 TX2T(1,1)=TY(NP)                                                  A4660
      GO TO 1819                                                        A4670
 1817 LX=NPM(I-1)                                                       A4680
      TX2T(1,I)=TX2T(LX,I-1)                                            A4690
 1819 CONTINUE                                                          A4700
      LM=NP+1                                                           A4710
      DO 833 I=1,NMB                                                    A4720
      LZ=NPM(I)                                                         A4730
      DO 833 J=1,LZ                                                     A4740
      TX2(LM)=TX2T(J,I)                                                 A4750
      LM=LM+1                                                           A4760
  833 CONTINUE                                                          A4770
      DO 5834 I=2,NPTT                                                  A4780
      IF(T-TTABLE(I)) 5835,5835,5834                                    A4790
 5835 DTS=DELTT(I-1)                                                    A4800
      IPRCT=IPRC(I-1)                                                   A4810
      DT=DELTT(I-1)/3600.0                                              A4820
      GO TO 5836                                                        A4830
 5834 CONTINUE                                                          A4840
      DTS=DELTT(NPTT)                                                   A4850
      IPRCT=IPRC(NPTT)                                                  A4860
      DT=DELTT(NPTT)/3600.0                                             A4870
 5836 ICT=ICT+1                                                         A4880
 5838 VLTEM=SAVY3                                                       A4890
      CALL ISOTHM(XV,TX2,1060. ,NP,SAVFIT)                              A4900
      SAVEIT=SAVEIT+XLSTV                                               A4910
      IF(SAVY3.LT.SAVFIT)SAVY3=SAVFIT                                   A4920
      IF(VLTEM.EQ.SAVY3)GO TO 839                                       A4930
      SAVX=T                                                            A4940
      SAVY1=XLSTI                                                       A4950
      SAVY2=TX2(NP)                                                     A4960
      CALL ISOTHM(XV,TX2,1460.,NP,SAVY4)                                A4970
  839 BLTEM=SAVY4X                                                      A4980
      CALL ISOTHM(XV,TX2,1460.,NP,WEKEEP)                               A4990
      WEKEEP=WEKEEP+XLSTV                                               A5000
      IF(SAVY4X.LT.WEKEEP)SAVY4X=WEKEEP                                 A5010
      IF(BLTEM.EQ.SAVY4X)GO TO 838                                      A5020
      SAVEXX=T                                                          A5030
      SAVY1X=XLSTI                                                      A5040
      SAVY2X=TX2(NP)                                                    A5050
      CALL ISOTHM(XV,TX2,1060.,NP,SAVY3X)                               A5060
  838 CONTINUE                                                          A5070
      IF(IPRCT-ICT) 835,835,840                                         A5080
  835 WRITE(6,837) T,QCONX,QRADX,VELX,XMDG(INT),XMDC,XMDT,XLSTI,QHW     A5090
  837 FORMAT(1H0,5HTIME=,                                               A5100
     1                     1PE12.5,2X,12HQCONVECTIVE=,1PE12.5,2X,11HQRADIAT A5110
     1IVE=,1PE12.5,2X,9HVELOCITY=,1PE12.5/1X,18HGAS ABLATION RATE=,1PE12  A5120
```

```
     2.5,2X,19HCHAR ABLATION RATE=,1PE12.5,2X,20HTOTAL ABLATION RATE=,1P
     3E12.5/1X,16HRECESSION DEPTH=,1PE12.5,2X,10HQHOT WALL=,1PE12.5)
 840 T=T+DTS
 841 IF(NPLOT.NE.1) GO TO 842
     CALL SAVE(ASAVE1,ASAVE2,ASAVE3,USEA,NXA,XLSTI,DTS,TLIM,T,VALUEA)
     CALL SAVE(BSAVE1,BSAVE2,BSAVE3,USEB,NXB,TX2(NP),DTS,TLIM,T,VALUEB)
     CALL ISOTHM(XV,TX2,1060.,NP,Y3)
     CALL SAVE(CSAVE1,CSAVE2,CSAVE3,USEC,NXC,Y3,DTS,TLIM,T,VALUEC)
     CALL ISOTHM(XV,TX2,1460.,NP,Y4)
     CALL SAVE(DSAVE1,DSAVE2,DSAVE3,USED,NXD,Y4,DTS,TLIM,T,VALUED)
     IF(USEA.NE.0.0)GO TO 9842
     IF(USEB.NE.0.0)GO TO 9842
     IF(USEC.NE.0.0)GO TO 9842
     IF(USED.NE.0.0)GO TO 9842
     GO TO 9843
9842 XPLOT=T-DTS
     YPLOT1=VALUEA
     IF(USEA.NE.0.0)YPLOT1=USEA
     YPLOT2=VALUEB
     IF(USEB.NE.0.0)YPLOT2=USEB
     YPLOT3=VALUEC
     IF(USEC.NE.0.0)YPLOT3=USEC
     YPLOT4=VALUED
     IF(USED.NE.0.0)YPLOT4=USED
     WRITE (11)XPLOT,YPLOT1,YPLOT2,YPLOT3,YPLOT4
9843 IF(ICTP.NE.0) GO TO 842
     ICTP=1
     XPLOT=T
     YPLOT1=XLSTI
     YPLOT2=TX2(NP)
     CALL ISOTHM(XV,TX2,1060.,NP,YPLOT3)
     CALL ISOTHM(XV,TX2,1460.,NP,YPLOT4)
     WRITE (11)XPLOT,YPLOT1,YPLOT2,YPLOT3,YPLOT4
 842 IF(IPRCT-ICT) 845,845,900
 845 WRITE(6,850) T
     IPCT=IPCT+1
     IF(IPCT.EQ.2)IPCT=0
     IF(IPCT.EQ.0)ICTP=0
 850 FORMAT(1H0,72HTEMPERATURE DISTRIBUTION IN HEAT SHIELD AT THE END O
     1F THE TIME STEP, T= ,1PE12.5,1X,7HSECONDS//)
     WRITE(6,860)
 860 FORMAT(4X,49HTEMPERATURE DISTRIBUTION IN THE ABLATING MATERIAL//)
     KKV=KKV+1
     WRITE(6,862) (TX2C(I),I=1,KKV)
 862 FORMAT(6X,1PE12.5,1P5E16.5)
     IJ=NP+1
     WRITE(6,864)
 864 FORMAT(//4X,49HTEMPERATURE DISTRIBUTION IN THE BACK-UP STRUCTURE//
     1)
     WRITE(6,862) (TX2(I),I=IJ,NPF)
     WRITE(6,865)
 865 FORMAT(//)
     ICT=0
 900 CONTINUE
     IF(T-TLIM) 750,750,905
 905 IF(NPLOT.NE.1) GO TO 909
     XAVY3=SAVY3-SAVY1/12.
```

```
      XAVY4X=SAVY4X-SAVY1X/12.                                          A5700
      IF(SAVX.EQ.XPLOT)GO TO 9005                                       A5710
      WRITE(11)SAVX,SAVY1,SAVY2,XAVY3,SAVY4                             A5720
 9005 IF(SAVEXX.EQ.XPLOT)GO TO 9006                                     A5730
      SAV4I=SAVY4X*12.                                                  A5760
 9006 SAV3I=SAVY3*12.                                                   A5750
      WRITE(11)SAVEXX,SAVY1X,SAVY2X,SAVY3X,XAVY4X                       A5740
      WRITE(6,929)SAV3I,SAV4I                                           A5770
  929 FORMAT(1H0,23HMAXIMUM 1060 ISOTHERM =E16.8,2X23HMAXIMUM 1460 ISOTH A5780
     1ERM =E16.8)                                                       A5790
      WRITE (11)STOP,STOP,STOP,STOP,STOP                                A5800
  909 IF(LPLOT.NE.NCASE)GO TO 911                                       A5810
      DATA END/6H  END /                                                A5820
      WRITE(11)END,END,END,END,END,END,END,END,END,END,END,END          A5830
      QUIT=8888.                                                        A5840
      WRITE(11)QUIT,QUIT,QUIT,QUIT,QUIT                                 A5850
      END FILE 11                                                       A5860
      REWIND 11                                                         A5870
  911 IF(TEST2) 910,930,930                                             A5880
  910 DO 920 JJK=1,NPF                                                  A5890
      TX1(JJK)=TEMDT(JJK)                                               A5900
      TX2(JJK)=TX1(JJK)                                                 A5910
      TUL1(K)=TX1(K)                                                    A5920
      TUL2(K)=TX1(K)                                                    A5930
  920 CONTINUE                                                          A5940
      IL=NP+1                                                           A5950
      DO 926 I=1,NMB                                                    A5960
      ILN=NPM(I)                                                        A5970
      DO 924 J=1,ILN                                                    A5980
      TX2T(J,I)=TEMDI(IL)                                               A5990
      IL=IL+1                                                           A6000
  924 CONTINUE                                                          A6010
  926 CONTINUE                                                          A6020
      GO TO 940                                                         A6030
  930 CALL TEMPD                                                        A6040
  940 T=TINT                                                            A6050
      DX=DXX                                                            A6060
      DTS=DELTT(1)                                                      A6070
      DT=DELTT(1)/3600.0                                                A6080
      VLV=VL                                                            A6090
      GO TO 50                                                          A6100
      END                                                               A6110
```

```
$IBFTC COEF
C     THIS SUBROUTINE DETERMINES THE COEFFICIENTS OF THE MATRIX
      SUBROUTINE COEFF(NPFT,SDOT)
C
      DIMENSION TITLE(12),HEADNG(12),XIDNT(12,12),TKC(20),XKC(20),
     1CPC(20),TKV(20),XKV(20),TCPV(20),CPV(20),TIME(300),QCON(300),
     2QRAD(300),VEL(300),XNPM(12),NKPB(12),NCPB(12),TXK(20,12),XK(20,12)
     3,TCP(20,12),CPX(20,12),RHOBX(12),XBM(12),EMFB(12),EMBB(12),HXX(12)
     4,GAPX(12),FTEST(12),BTEST(12),TEMDI(200),TX1(200),TX2(200),
     5TX2T(10,12),TUL1(200),TUL2(200),HX(50),TW(50),IR(50),IR1(50),
     6IR2(50),TUL(50),IEM(50),TY(200),A(200),B(200),C(200),D(200),
     7R(50),RHO(50),CP(50),DXB(12),XKB(10,12),CPB(10,12),XMDG(50),
     8YK(50),AB(10,12),BB(10,12),CB(10,12),DB(10,12),SB(10,12),
     9RB1(10,12),RB2(10,12),H(12),S(50),NPM(12)
      DIMENSION TTUL(50),RHOY1(50),RHOY2(50),DRHO(50),TCPC(20)
C
      COMMON TKC,XKC,TCPC,CPC,TKV,XKV,TCPV,CPV,XNPM,RHOBX,XBM,EMBB,
     1EMFB,NKPB,NCPB,TXK,XK,TCP,CPX,NPM,GAPX,FTEST,BTEST,TEMDI,TX1,
     2TX2,TX2T,TUL,TUL1,TUL2,IR,IR1,IR2,A,B,C,D,S,R,AB,BB,CB,DB,SB,
     3RB1,RB2,TY,RHOY1,RHOY2,XMDG,RHO,CP,YK,XKB,CPB,DXB,DT,XLOST,
     4TABL,TCHAR,TREC,RHOV,RHOC,FBLOW,EMV,EMC,H300,NKC,NCPC,NKV,NCPV,
     5NP,NMB,NPBS,NPF,TEST2,TEMPI,TX0,TENV,HENV,FENV,QLOSS,TLIM,TINT
      COMMON I1,I2,I3,I4,I5,I6,QIN,INT,DX,XMT,TL,VL,BL,DMP,ERR1,ERR2,
     1ERR3,ERR4,HV,VPT,CHARK,CHARC,ABLK,ABLC,XMDC,H
C
      CALL PROP
      YNP=NP
      S(INT)=(RHO(INT)*DX*CP(INT))/(2.0*DT)
      R(INT)=(1.0)/((DX/2.0)*((1.0/YK(INT))+(1.0/YK(INT+1))))
      A(INT)=0.0
      B(INT)=(-((XMDG(INT)+XMDC)*CP(INT)+S(INT)+R(INT)-RHO(INT)*CP(INT)
     1*(SDOT/(2.0*(YNP-1.0)))))
      C(INT)=XMDG(INT+1)*CP(INT+1)+R(INT)+RHO(INT+1)*CP(INT+1)*SDOT
     1*((YNP-1.5)/(YNP-1.0))
      D(INT)=(-(QIN+S(INT)*TX2(INT))) +(XMDG(INT)-XMDG(INT+1))*HV
      NPP=NP-1
      JNT=INT+1
      DO 10 I=JNT,NPP
      XI=I
      S(I)=(RHO(I)*DX*CP(I))/DT
      R(I)=(1.0)/((DX/(2.0*YK(I)))+(DX/(2.0*YK(I+1))))
      A(I)=R(I-1)
      B(I)=(-(XMDG(I)*CP(I)+R(I-1)+R(I)+S(I)+ RHO(I)*CP(I)*SDOT*((YNP-XI
     1-0.5)/(YNP-1.0))))
      C(I)=XMDG(I+1)*CP(I+1)+R(I)+RHO(I+1)*CP(I+1)*SDOT*((YNP-XI-0.5)
     1/(YNP-1.0))
      D(I)=(-(S(I)*TX2(I))) +(XMDG(I)-XMDG(I+1))*HV
   10 CONTINUE
      R(NP)=(1.0)/((DXB(1)    /(2.0*XKB(1,1)))+(DXB(1)   /(2.0*XKB(2,1))))
      S(NP)=(RHO(NP)*DX*CP(NP)+RHOBX(1)* CPB(1,1)*DXB(1))/(2.0*DT)
      A(NP)=R(NP-1)
      B(NP)=(-(XMDG(NP)*CP(NP)+R(NP-1)+R(NP)+S(NP)))
      C(NP)=R(NP)
      D(NP)=(-S(NP)*TX2(NP)) +XMDG(NP)*HV
      DO 200 I=1,NMB
      IF(I-1) 20,20,30
   20 AB(1,I)=A(NP)
      BB(1,I)=B(NP)
      CB(1,I)=C(NP)
      DB(1,I)=D(NP)
```

```
      GO TO 65
   30 L=NPM(I-1)
      IF(FTEST(I)) 45,40,45
   40 SB(1,I)=(RHOBX(I)*CPB(1,I)*DXB(I)+RHOBX(I-1)*CPB(L,I-1)*DXB(I-1))/
     1(2.0*DT)
      RB1(1,I)=(1.0)/((DXB(I-1)/(2.0*XKB(L,I-1)))+(DXB(I-1)/(2.0*XKB(L-1
     1,I-1))))
      RB2(1,I)=(1.0)/((DXB(I)/(2.0*XKB(1,I)))+(DXB(I)/(2.0*XKB(2,I))))
      AB(1,I)=RB1(1,I)
      BB(1,I)=(-(RB1(1,I)+RB2(1,I)+SB(1,I)))
      CB(1,I)=RB2(1,I)
      DB(1,I)=(-(SB(1,I)*TX2T(1,I)))
      GO TO 65
   45 IF(FTEST(I)) 50,40,55
   50 G=(1.73E-09)/(1.0/EMBB(I-1)+1.0/EMFB(I)-1.0)
      GO TO 60
   55 G=0.0
   60 SB(1,I)=(RHOBX(I)*CPB(1,I)*DXB(I))/(2.0*DT)
      RB2(1,I)=(1.0)/((DXB(I)/(2.0*XKB(1,I)))+(DXB(I)/(2.0*XKB(2,I))))
      AB(1,I)=H(I-1)+4.0*G*(TX2T(L,I-1)**3)
      BB(1,I)=(-(H(I-1)+4.0*G*(TX2T(1,I   )**3)+RB2(1,I)+SB(1,I)))
      CB(1,I)=RB2(1,I)
      DB(1,I)=3.0*G*((TX2T(L,I-1)**4)-(TX2T(1,I)**4))-SB(1,I)*TX2T(1,I)
   65 LF=NPM(I)-1
      DO 100 J=2,LF
      SB(J,I)=(RHOBX(I)*CPB(J,I)*DXB(I))/DT
      RB1(J,I)=(1.0)/((DXB(I)/(2.0*XKB(J-1,I)))+(DXB(I)/(2.0*XKB(J,I))))
      RB2(J,I)=(1.0)/((DXB(I)/(2.0*XKB(J+1,I)))+(DXB(I)/(2.0*XKB(J,I))))
      AB(J,I)=RB1(J,I)
      BB(J,I)=(-(RB1(J,I)+RB2(J,I)+SB(J,I)))
      CB(J,I)=RB2(J,I)
      DB(J,I)=(-(SB(J,I)*TX2T(J,I)))
  100 CONTINUE
      IF(I-NMB) 110,250,250
  110 LNF=NPM(I)
      IF(BTEST(I)) 120,115,120
  115 SB(LNF,I)=(RHOBX(I)*CPB(LNF,I)*DXB(I)+RHOBX(I+1)*CPB(1,I+1)*DXB(I+
     11))/(2.0*DT)
      RB1(LNF,I)=(1.0)/((DXB(I)/(2.0*XKB(LNF-1,I)))+(DXB(I)/(2.0*XKB(LNF
     1,I))))
      RB2(LNF,I)=(1.0)/((DXB(I+1)/(2.0*XKB(1,I+1)))+(DXB(I+1)/
     1(2.0*XKB(2,I+1))))
      AB(LNF,I)=RB1(LNF,I)
      BB(LNF,I)=(-(RB1(LNF,I)+RB2(LNF,I)+SB(LNF,I)))
      CB(LNF,I)=RB2(LNF,I)
      DB(LNF,I)=(-(SB(LNF,I)*TX2T(LNF,I)))
      GO TO 200
  120 IF(BTEST(I)) 125,115,127
  125 G=(1.73E-09)/(1.0/EMBB(I)+1.0/EMFB(I+1)-1.0)
      GO TO 130
  127 G=0.0
  130 SB(LNF,I)=(RHOBX(I)*CPB(LNF,I)*DXB(I))/(2.0*DT)
      RB1(LNF,I)=(1.0)/((DXB(I)/(2.0*XKB(LNF-1,I)))+(DXB(I)/(2.0*XKB(LNF
     1,I))))
      AB(LNF,I)=RB1(LNF,I)
      BB(LNF,I)=(-(RB1(LNF,I)+H(I)+SB(LNF,I)+4.0*G*(TX2T(LNF,I)**3)))
      CB(LNF,I)=H(I)+4.0*G*(TX2T(1,I+1)**3)
      DB(LNF,I)=3.0*G*((TX2T(1,I+1)**4)-(TX2T(LNF,I)**4))-SB(LNF,I)*TX2T
     1(LNF,I)
  200 CONTINUE
```

```
250 MN=NPM(NMB)
    IF(QLOSS) 270,260,270
260 SB(MN,NMB)=(RHOBX(NMB)*CPB(MN,NMB)*DXB(NMB))/(2.0*DT)
    RB1(MN,NMB)=(1.0)/((DXB(NMB)/(2.*XKB(MN-1,NMB)))+(DXB(NMB)/(2.0*XK
   1B(MN,NMB))))
    AB(MN,NMB)=RB1(MN,NMB)
    BB(MN,NMB)=(-(RB1(MN,NMB)+SB(MN,NMB)))
    CB(MN,NMB)=0.0
    DB(MN,NMB)=(-(SB(MN,NMB)*TX2T(MN,NMB)))
    GO TO 280
270 SB(MN,NMB)=(RHOBX(NMB)*CPB(MN,NMB)*DXB(NMB))/(2.0*DT)
    RB1(MN,NMB)=(1.0)/((DXB(NMB)/(2.0*XKB(MN-1,NMB)))+(DXB(NMB)/(2.0*X
   1KB(MN,NMB))))
    AB(MN,NMB)=RB1(MN,NMB)
    BB(MN,NMB)=(-(RB1(MN,NMB)+HENV+(1.73E-09)*FENV*4.0*(TX2T(MN,NMB)**
   13)+SB(MN,NMB)))
    CB(MN,NMB)=0.0
    DB(MN,NMB)=(-(HENV*TENV+FENV*(1.73E-09)*((TENV**4)+3.0*(TX2T(MN,NM
   1B)**4))+SB(MN,NMB)*TX2T(MN,NMB)))
280 L=NP+1
    DO 300 I=1,NMB
    K=NPM(I)
    IF(I.EQ.1) GO TO 282
    IF(GAPX(I-1).EQ.0.) GO TO 282
    KT=1
    GO TO 285
282 KT=2
285 DO 290 J=KT,K
    A(L)=AB(J,I)
    B(L)=BB(J,I)
    C(L)=CB(J,I)
    D(L)=DB(J,I)
    IF(DMP) 289,289,286
286 WRITE(6,287) AB(J,I),BB(J,I),CB(J,I),DB(J,I),J,I,A(L),B(L),C(L),D(
   1L),L
287 FORMAT(1H0,8HAB(J,I)=,1PE12.5,2X,8HBB(J,I)=,1PE12.5,2X,8HCB(J,I)=,
   11PE12.5,2X,8HDB(J,I)=,1PE12.5,2X,2HJ=,I3,2X,2HI=,I3/1X,5HA(L)=,1PE
   212.5,2X,5HB(L)=,1PE12.5,2X,5HC(L)=,1PE12.5,2X,5HD(L)=,1PE12.5,2X,2
   3HL=,I3)
289 L=L+1
290 CONTINUE
300 CONTINUE
    NPFT=L-1
    RETURN
    END
```

```
$IBFTC PRP
C       THIS SUBROUTINE DETERMINES THE PHYSICAL PROPERTIES OF THE
C         HEAT SHIELD STRUCTURE
        SUBROUTINE PROP
C
        DIMENSION TITLE(12),HEADNG(12),XIDNT(12,12),TKC(20),XKC(20),
       1CPC(20),TKV(20),XKV(20),TCPV(20),CPV(20),TIME(300),QCON(300),
       2QRAD(300),VEL(300),XNPM(12),NKPB(12),NCPB(12),TXK(20,12),XK(20,12)
       3,TCP(20,12),CPX(20,12),RHOBX(12),XBM(12),EMEB(12),EMBB(12),HXX(12)
       4,GAPX(12),FTEST(12),BTEST(12),TEMDI(200),TX1(200),TX2(200),
       5TX2T(10,12),TUL1(200),TUL2(200),HX(50),TW(50),IR(50),IR1(50),
       6IR2(50),TUL(50),IEM(50),TY(200),A(200),B(200),C(200),D(200),
       7R(50),RHO(50),CP(50),DXB(12),XKB(10,12),CPB(10,12),XMDG(50),
       8YK(50),AB(10,12),BB(10,12),CB(10,12),DB(10,12),SB(10,12),
       9RB1(10,12),RB2(10,12),H(12),S(50),NPM(12)
        DIMENSION TTUL(50),RHOY1(50),RHOY2(50),DRHO(50),TCPC(20)
C
        COMMON TKC,XKC,TCPC,CPC,TKV,XKV,TCPV,CPV,XNPM,RHOBX,XBM,EMBB,
       1EMEB,NKPB,NCPB,TXK,XK,TCP,CPX,NPM,GAPX,FTEST,BTEST,TEMDI,TX1,
       2TX2,TX2T,TUL,TUL1,TUL2,IR,IR1,IR2,A,B,C,D,S,R,AB,BB,CB,DB,SB,
       3RB1,RB2,TY,RHOY1,RHOY2,XMDG,RHO,CP,YK,XKB,CPB,DXB,DT,XLOST,
       4TABL,TCHAR,TREC,RHOV,RHOC,FBLOW,FMV,EMC,H300,NKC,NCPC,NKV,NCPV,
       5NP,NMB,NPBS,NPF,TEST2,TEMPI,TX0,TENV,HENV,FENV,QLOSS,TLIM,TINT
        COMMON I1,I2,I3,I4,I5,I6,QIN,INT,DX,XMT,TL,VL,BL,DMP,ERR1,ERR2,
       1ERR3,ERR4,HV,VPT,CHARK,CHARC,ABLK,ABLC,XMDC,H
C
        KINT=INT
        DO 170 I=KINT,NP
   10 IF(IR(I)) 12,12,100
   12 TUL(I)=AMAX1(TX1(I),TX2(I))
        IF(TUL(I).LE.TABL) GO TO 20
        IR(I)=1
        GO TO 100
   20 IF(I1-1) 25,25,21
   21 IF(I1-NKV) 22,22,25
   22 IF(TX2(I)-TKV(I1)) 35,55,30
   25 WRITE(6,26) TX2(I)
   26 FORMAT(1H0,87H THE RANGE OF ONE OF THE ABLATION PROPERTY CURVE FIT
      1S WAS EXCEEDED AT A TEMPERATURE OF ,1PE12.5)
        ERR2=1.0
        GO TO 355
   30 I1=I1+1
        GO TO 21
   35 IF(TX2(I)-TKV(I1-1)) 40,55,50
   40 I1=I1-1
        GO TO 20
   50 YK(I)=XKV(I1-1)+((XKV(I1)-XKV(I1-1))/(TKV(I1)-TKV(I1-1)))
      1*(TX2(I)-TKV(I1-1))
        GO TO 60
   55 YK(I)=XKV(I1)
   60 IF(I2-1) 25,25,61
   61 IF(I2-NCPV) 62,62,25
   62 IF(TX2(I)-TCPV(I2)) 70,85,65
   65 I2=I2+1
        GO TO 61
   70 IF(TX2(I)-TCPV(I2-1)) 75,85,80
   75 I2=I2-1
```

```
      GO TO 60
   80 CP(I)=CPV(I2-1)+((CPV(I2)-CPV(I2-1))/(TCPV(I2)-TCPV(I2-1)))
     1*(TX2(I)-TCPV(I2-1))
      GO TO 90
   85 CP(I)=CPV(I2)
   90 RHO(I)=RHOV
      GO TO 170
  100 TUL(I)=AMAX1(TUL(I),TX2(I))
      IF(TUL(I)-TCHAR) 110,110,115
  110 RHO(I)=RHOV+(RHOV-RHOC)*((TUL(I)-TABL)/(TABL-TCHAR))
      YK(I)=CHARK+(ABLK-CHARK)*((RHO(I)-RHOC)/(RHOV-RHOC))
      CP(I)=CHARC+(ABLC-CHARC)*((RHO(I)-RHOC)/(RHOV-RHOC))
      GO TO 170
  115 IF(VPT) 116,116,117
  116 TTUL(I)=TUL(I)
      GO TO 120
  117 TTUL(I)=TX2(I)
  120 IF(I3-1) 25,25,121
  121 IF(I3-NKC) 122,122,25
  122 IF(TTUL(I)-TKC(I3)) 124,135,123
  123 I3=I3+1
      GO TO 121
  124 IF(TTUL(I)-TKC(I3-1)) 125,135,130
  125 I3=I3-1
      GO TO 120
  130 YK(I)=XKC(I3-1)+((XKC(I3)-XKC(I3-1))/(TKC(I3)-TKC(I3-1)))
     1*(TTUL(I)-TKC(I3-1))
      GO TO 140
  135 YK(I)=XKC(I3)
  140 IF(I4-1) 25,25,141
  141 IF(I4-NCPC) 142,142,25
  142 IF(TTUL(I)-TCPC(I4)) 150,165,145
  145 I4=I4+1
      GO TO 141
  150 IF(TTUL(I)-TCPC(I4-1)) 155,165,160
  155 I4=I4-1
      GO TO 140
  160 CP(I)=CPC(I4-1)+((CPC(I4)-CPC(I4-1))/(TCPC(I4)-TCPC(I4-1)))
     1*(TTUL(I)-TCPC(I4-1))
      GO TO 166
  165 CP(I)=CPC(I4)
  166 RHO(I)=RHOC
  170 CONTINUE
C
C     DETERMINATION OF PROPER BACK-UP SHIELD MATERIAL PROPERTY
C
      DO 300 I=1,NMB
      DXB(I)=XBM(I)/((XNPM(I)-1.0)*12.0)
      LKP=NKPB(I)
      LCP=NCPB(I)
      NN=NPM(I)
      DO 280 J=1,NN
  200 IF(I5-1) 203,203,201
  201 IF(I5-LKP) 202,202,203
  202 IF(TX2T(J,I)-TXK(I5,I)) 206,220,205
  203 WRITE(6,204) I,TX2T(J,I)
  204 FORMAT(1H0,32H THE RANGE OF ONE OF THE NUMBER ,I2,71H BACKUP STRUC
```

```
     1TURE PROPERTY CURVE FITS WAS EXCEEDED AT A TEMPERATURE OF ,1PE12.5
     2)
      ERR2=1.0
      GO TO 355
  205 I5=I5+1
      GO TO 201
  206 IF(TX2T(J,I)-TXK(I5-1,I)) 210,220,215
  210 I5=I5-1
      GO TO 200
  215 XKB(J,I)=XK(I5-1,I)+((XK(I5,I)-XK(I5-1,I))/(TXK(I5,I)-TXK(I5-1,I))
     1)*(TX2T(J,I)-TXK(I5-1,I))
      GO TO 230
  220 XKB(J,I)=XK(I5,I)
  230 IF(I6-1) 203,203,231
  231 IF(I6-LCP) 232,232,203
  232 IF(TX2T(J,I)-TCP(I6,I)) 234,245,233
  233 I6=I6+1
      GO TO 231
  234 IF(TX2T(J,I)-TCP(I6-1,I)) 235,245,240
  235 I6=I6-1
      GO TO 230
  240 CPB(J,I)=CPX(I6-1,I)+((CPX(I6,I)-CPX(I6-1,I))/(TCP(I6,I)-TCP(I6-1,
     1I)))*(TX2T(J,I)-TCP(I6-1,I))
      GO TO 280
  245 CPB(J,I)=CPX(I6,I)
  280 CONTINUE
      I5=2
      I6=2
  300 CONTINUE
  310 IF(DMP) 355,355,320
  320 WRITE(6,330)
  330 FORMAT(/1X,32H PROPERTIES OF ABLATION MATERIAL/)
      WRITE(6,335)
  335 FORMAT(/5X,5HYK(I),9X,5HCP(I),9X,6HRHO(I)/)
      WRITE(6,340) (YK(I),CP(I),RHO(I),I=1,NP)
  340 FORMAT(2X,1PE12.5,2X,1PE12.5,2X,1PE12.5)
      WRITE(6,345)
  345 FORMAT(//1X,32H PROPERTIES OF BACK-UP STRUCTURE/)
      WRITE(6,347)
  347 FORMAT(/5X,8HYKB(J,I),7X,8HCPB(J,I),7X,8HRHOBX(I),7X,7HEMFB(I),8X,
     17HEMBB(I),9X,6HDXB(I)/)
      DO 350 I=1,NMB
      KL=NPM(I)
      DO 349 J=1,KL
      WRITE(6,348) XKB(J,I),CPB(J,I),RHOBX(I),EMFB(I),EMBB(I),DXB(I)
  348 FORMAT(3X,1PE12.5,3X,1PE12.5,3X,1PE12.5,3X,1PE12.5,3X,1PE12.5,3X,1
     1PE12.5)
  349 CONTINUE
  350 CONTINUE
  355 RETURN
      END
```

```
$IBFTC ABL
C      THIS SUBROUTINE DETERMINES THE MASS FLOW RATE FROM THE
C        ABLATING NODES
      SUBROUTINE ABLATE
C
       DIMENSION TITLE(12),HEADNG(12),XIDNT(12,12),TKC(20),XKC(20),
     1CPC(20),TKV(20),XKV(20),TCPV(20),CPV(20),TIME(300),QCON(300),
     2QRAD(300),VEL(300),XNPM(12),NKPB(12),NCPB(12),TXK(20,12),XK(20,12)
     3,TCP(20,12),CPX(20,12),RHOBX(12),XBM(12),EMFB(12),EMBR(12),HXX(12)
     4,GAPX(12),FTEST(12),BTEST(12),TEMDI(200),TX1(200),TX2(200),
     5TX2T(10,12),TUL1(200),TUL2(200),HX(50),TW(50),IR(50),IR1(50),
     6IR2(50),TUL(50),IEM(50),TY(200),A(200),B(200),C(200),D(200),
     7R(50),RHO(50),CP(50),DXP(12),XKB(10,12),CPB(10,12),XMDG(50),
     8YK(50),AB(10,12),BB(10,12),CB(10,12),DB(10,12),SB(10,12),
     9RB1(10,12),RB2(10,12),H(12),S(50),NPM(12)
       DIMENSION TTUL(50),RHOY1(50),RHOY2(50),DRHO(50),TCPC(20)
C
       COMMON TKC,XKC,TCPC,CPC,TKV,XKV,TCPV,CPV,XNPM,RHOBX,XBM,EMBR,
     1EMFB,NKPB,NCPB,TXK,XK,TCP,CPX,NPM,GAPX,FTEST,BTEST,TEMDI,TX1,
     2TX2,TX2T,TUL,TUL1,TUL2,IR,IR1,IR2,A,B,C,D,S,R,AB,BB,CB,DB,SB,
     3RB1,RB2,TY,RHOY1,RHOY2,XMDG,RHO,CP,YK,XKB,CPB,DXB,DT,XLOST,
     4TABL,TCHAR,TREC,RHOV,RHOC,EBLOW,EMV,EMC,H300,NKC,NCPC,NKV,NCPV,
     5NP,NMB,NPBS,NPF,TEST2,TEMPI,TX0,TENV,HENV,EENV,QLOSS,TLIM,TINT
       COMMON I1,I2,I3,I4,I5,I6,QIN,INT,DX,XMT,TL,VL,BL,DMP,ERR1,ERR2,
     1ERR3,ERR4,HV,VPT,CHARK,CHARC,ABLK,ABLC,XMDC,H
C
       XMT=0.0
       LINT=INT
       KI=NP
       IF(DMP) 8,8,3
    3  WRITE(6,5)
    5  FORMAT(//1X,29HMASS FLOW FROM ABLATING NODES//)
    8  DO 200 KKI=LINT,NP
       IF(IR1(KI)) 11,11,12
   11  IF(TX1(KI).LE.TABL) GO TO 9
   12  TUL1(KI)=AMAX1(TUL1(KI),TX1(KI))
       IR1(KI)=1
       GO TO 20
    9  IF(TX1(KI)-TABL) 10,10,20
   10  RHOY1(KI)=RHOV
       GO TO 50
   20  IF(TUL1(KI)-TCHAR) 40,30,30
   30  RHOY1(KI)=RHOC
       GO TO 50
   40  RHOY1(KI)=RHOV+(RHOV-RHOC)*((TUL1(KI)-TABL)/(TABL-TCHAR))
   50  IF(IR2(KI)) 52,52,54
   52  IF(TX2(KI).LE.TABL) GO TO 56
   54  TUL2(KI)=AMAX1(TUL2(KI),TX2(KI))
       IR2(KI)=1
       GO TO 70
   56  IF(TX2(KI)-TABL) 60,60,70
   60  RHOY2(KI)=RHOV
       GO TO 95
   70  IF(TUL2(KI)-TCHAR) 90,80,80
   80  RHOY2(KI)=RHOC
       GO TO 95
   90  RHOY2(KI)=RHOV+(RHOV-RHOC)*((TUL2(KI)-TABL)/(TABL-TCHAR))
```

```
 95 DRHO(KI)=((RHOY1(KI)-RHOY2(KI))/DT)*DX
    IF(KI-NP) 97,96,96
 96 DRHO(KI)=DRHO(KI)/2.0
    GO TO 98
 97 IF(KI-INT) 96,96,98
 98 IF(DRHO(KI)) 110,120,120
110 DRHO(KI)=0.0
120 XMT=XMT+DRHO(KI)
    XMDG(KI)=XMT
    IF(DMP) 190,190,150
150 WRITE(6,160) XMDG(KI),DRHO(KI),RHOY2(KI),RHOY1(KI)
160 FORMAT(1X,5HXMDG=,1PE12.5,2X,5HDRHO=,1PE12.5,2X,6HRHOY2=,1PE12.5,2
   1X,6HRHOY1=,1PE12.5)
190 KI=KI-1
200 CONTINUE
    RETURN
    END
```

```
$IBFTC OXID
C
C     THIS SUBROUTINE CALCULATES THE HEATING RATE DUE TO COMBUSTION
C     IT IS ASSUMED THAT OXYGEN AND CARBON REACT  TO FORM CO ONLY.
C
      SUBROUTINE OXIDAT(XMDO,QOXID)
C
      QOXID=XMDO*4000.0/3600.0
      QOXID=0.0
      RETURN
      END
```

```
$IBFTC SWUFT
C      THIS SUBROUTINE DETERMINES THE FORWARD TIME STEP TEMPERATURES
C      BY SOLVING THE TRI-DIAGONAL MATRIX
       SUBROUTINE SWUFT(A,B,C,D,T,N,DMP)
       DIMENSION A(200),B(200),C(200),D(200),T(200),CP(200),DP(200)
       CP(1)=C(1)/B(1)
       DP(1)=D(1)/B(1)
       DO 100 I=2,N
       CP(I)=C(I)/(B(I)-A(I)*CP(I-1))
       DP(I)=(D(I)-A(I)*DP(I-1))/(B(I)-A(I)*CP(I-1))
  100  CONTINUE
       T(N)=DP(N)
       NM1=N-1
       DO 200 J=1,NM1
       I=N-J
       T(I)=DP(I)-CP(I)*T(I+1)
  200  CONTINUE
       IF(DMP) 300,300,250
  250  WRITE(6,260)
  260  FORMAT(//1X,43HCOEFFICIENTS CALCULATED BY SUBROUTINE SWUFT//)
       WRITE(6,270)
  270  FORMAT(6X,5HCP(I),10X,5HDP(I),10X,4HT(I)/)
       WRITE(6,275) (CP(I),DP(I),T(I),I=1,N)
  275  FORMAT(2X,1PE12.5,2X,1PE12.5,2X,1PE12.5)
  300  RETURN
       END
```

```
$IBFTC REC
C
C     THIS SUBROUTINE DETERMINES THE FRONT FACE LOCATION AND CHAR MASS
C     REMOVAL RATE
C
      SUBROUTINE RECESS(XMDC,XLOST,TREC,DT,RHOC,TS,SR,TX2,NREC,NRS,ERR5,
     1SX0,SDOT,DMP)
C
      DIMENSION TS(50),SR(50)
      IF(TX2-TREC) 10,20,20
   10 XMDC=0.0
      XLOST=0.0
      SDOT=0.0
      GO TO 60
   20 IF(NRS-1)25,25,21
   21 IF(NRS-NREC) 22,22,25
   22 IF(TX2-TS(NRS)) 32,40,30
   25 WRITE(6,26) TX2
   26 FORMAT(1H0,75H THE RANGE OF THE SURFACE RECESSION TABLE WAS EXCEED
     1ED AT A TEMPERATURE OF ,1PE12.5)
      ERR5=1.0
      GO TO 60
   30 NRS=NRS+1
      GO TO 21
   32 IF(TX2-TS(NRS-1)) 34,40,36
   34 NRS=NRS-1
      GO TO 20
   36 SX=SR(NRS-1)+((SR(NRS)-SR(NRS-1))/(TS(NRS)-TS(NRS-1)))
     1*(TX2-TS(NRS-1))
      GO TO 50
   40 SX=SR(NRS)
   50 XLOST=300.0*SX*DT
      XMDC=(XLOST*RHOC)/DT
      SDOT=SX*300.0
      IF(DMP) 60,60,52
   52 WRITE(6,54) SX,XLOST,XMDC
   54 FORMAT(1H0,3HSX=,1PE12.5,3X,6HXLOST=,1PE12.5,3X,5HXMDC=,1PE12.5)
   60 RETURN
      END
```

```
$IBFTC TEMP
C      THIS SUBROUTINE DETERMINES THE INITIAL TEMPERATURE DISTRIBUTION
C      IN THE HEAT SHIELD STRUCTURE
       SUBROUTINE TEMPD
C
       DIMENSION TITLE(12),HEADNG(12),XIDNT(12,12),TKC(20),XKC(20),
      1CPC(20),TKV(20),XKV(20),TCPV(20),CPV(20),TIME(300),QCON(300),
      2QRAD(300),VEL(300),XNPM(12),NKPB(12),NCPB(12),TXK(20,12),XK(20,12)
      3,TCP(20,12),CPX(20,12),RHOBX(12),XBM(12),EMFB(12),EMBB(12),HXX(12)
      4,GAPX(12),FTEST(12),BTEST(12),TEMDI(200),TX1(200),TX2(200),
      5TX2T(10,12),TUL1(200),TUL2(200),HX(50),TW(50),IR(50),IR1(50),
      6IR2(50),TUL(50),IEM(50),TY(200),A(200),B(200),C(200),D(200),
      7R(50),RHO(50),CP(50),DXB(12),XKB(10,12),CPB(10,12),XMDG(50),
      8YK(50),AB(10,12),BB(10,12),CB(10,12),DB(10,12),SB(10,12),
      9RB1(10,12),RB2(10,12),H(12),S(50),NPM(12)
       DIMENSION TTUL(50),RHOY1(50),RHOY2(50),DRHO(50),TCPC(20)
C
       COMMON TKC,XKC,TCPC,CPC,TKV,XKV,TCPV,CPV,XNPM,RHOBX,XBM,EMBB,
      1EMFB,NKPB,NCPB,TXK,XK,TCP,CPX,NPM,GAPX,FTEST,BTEST,TEMDI,TX1,
      2TX2,TX2T,TUL,TUL1,TUL2,IR,IR1,IR2,A,B,C,D,S,R,AB,BB,CB,DB,SB,
      3RB1,RB2,TY,RHOY1,RHOY2,XMDG,RHO,CP,YK,XKB,CPB,DXB,DT,XLOST,
      4TABL,TCHAR,TREC,RHOV,RHOC,FBLOW,FMV,EMC,H300,NKC,NCPC,NKV,NCPV,
      5NP,NMB,NPBS,NPF,TEST2,TEMPI,TX0,TENV,HENV,FENV,QLOSS,TLIM,TINT
       COMMON I1,I2,I3,I4,I5,I6,QIN,INT,DX,XMT,TL,VL,BL,DMP,ERR1,ERR2,
      1ERR3,ERR4,HV,VPT,CHARK,CHARC,ABLK,ABLC,XMDC,H
C
       X=0.0
       IF(TEST2) 300,100,200
   100 DO 150 L=1,NPF
       TX1(L)=TEMPI
       TX2(L)=TEMPI
       TUL1(L)=TX1(L)
       TUL2(L)=TX2(L)
       TEMDI(L)=TEMPI
   150 CONTINUE
       DO 160 I=1,NMB
       JN=NPM(I)
       DO 155 M=1,JN
       TX2T(M,I)=TEMPI
   155 CONTINUE
   160 CONTINUE
       GO TO 320
   200 DO 220 L=1,NP
       TEMDI(L)=TX0+((TENV-TX0)/TL)**X
       TX1(L)=TEMDI(L)
       TX2(L)=TX1(L)
       TUL1(L)=TX1(L)
       TUL2(L)=TX1(L)
       X=X+DX
   220 CONTINUE
       L=NP+1
       DO 270 I=1,NMB
       KJ=NPM(I)
       DO 250 J=1,KJ
       TEMDI(L)=TX0+((TENV-TX0)/TL)**X
       TX1(L)=TEMDI(L)
       TX2(L)=TEMDI(L)
```

```
      TX2T(J,I)=TEMPI(L)
      X=X+DXB(I)
      L=L+1
  250 CONTINUE
      X=X+(GAPX(I)/12.0)
  270 CONTINUE
      GO TO 320
C     AN ARBRITARY TEMPERATURE DISTRIBUTION CAN BE READ IN FROM INPUT
C      DATA IF TEST2 IS A NEGATIVE NUMBER
  300 WRITE(6,310)
  310 FORMAT(1H0,79H THE VALUE OF TEST2 WAS NEGATIVE, SUBROUTINE TEMPD S
     1HOULD NOT HAVE BEEN CALLED.)
      ERR1=1.0
  320 RETURN
      END
```

```
$IBFTC DON2
C      THIS SUBROUTINE DETERMINES THE TEMPERATURE OF POINTS A FIXED
C      DISTANCE FROM A REFERENCE PLANE FROM THE TEMPERATURES CALCULATED
C      IN A VARYING THICKNESS
C
       SUBROUTINE DON2(XLOST,XARRAY,TARRAY,NA,XNODE,TEMP,XNODEV,KK,XLSTV,
      1DX)
C
       DIMENSION XARRAY(50),TARRAY(50),XNODE(50),TEMP(50),XNODEV(50)
C
       K=0
       DXT=0.0
       DO 100 I=1,NA
       IF(XLSTV.LE.DXT) GO TO 150
       K=K+1
   100 DXT=DXT+DX
   150 KK=NA-K
       XK=K
       XNODEV(1)=XLSTV
       TEMP(1)=TARRAY(1)
       DO 200 I=1,KK
       XNODE(I)=XK*DX-XLSTV
       CALL DISCT3(XNODE(I),XARRAY,TARRAY,NA,TEMP(I+1) )
       XNODEV(I+1)=XK*DX
   200 XK=XK+1.0
       RETURN
       END
```

```
$IBFTC UINTRP
      SUBROUTINE UINTRP(X,XTBL,Y,YTBL,N,J)
      DIMENSION XTBL(50),YTBL(50)
      I=J
      IF(I.GT.N.OR.I.LT.2) I=2
   10 IF(XTBL(I-1).LE.X.AND.X.LE.XTBL(I)) GO TO 40
      IF(X.GT.XTBL(I)) GO TO 30
   20 I=I-1
      IF(I.GE.2) GO TO 10
      I=2
      GO TO 40
   30 I=I+1
      IF(I.LE.N) GO TO 10
      I=N
   40 FRACT=(X-XTBL(I-1))/(XTBL(I)-XTBL(I-1))
      Y=YTBL(I-1)+(YTBL(I)-YTBL(I-1))*FRACT
      RETURN
      END
```

```
$IBFTC ISOT
      SUBROUTINE ISOTHM(DEPTH,TEMP,BOND,N,ANS)
      DIMENSION DEPTH(1),TEMP(1)
      ANS=-1.
      K=N-1
      DO 100 I=1,K
      IF(TEMP(I)-BOND)2,1,3
    1 ANS=DEPTH(I)
      GO TO 100
    2 IF(TEMP(I+1)-BOND)100,100,4
    4 ANS=DEPTH(I+1)-(TEMP(I+1)-BOND)*(DEPTH(I+1)-DEPTH(I))/(TEMP(I+1)-
     1TEMP(I))
      GO TO 100
    3 IF(TEMP(I+1)-BOND)5,100,100
    5 ANS=(TEMP(I)-BOND)*(DEPTH(I+1)-DEPTH(I))/(TEMP(I)-TEMP(I+1))+DEPTH
     1(I)
  100 CONTINUE
      IF(BOND.EQ.TEMP(N))ANS=DEPTH(N)
      RETURN
      END
```

```
$IBFTC SAVE
      SUBROUTINE SAVE(SAVE1,SAVE2,SAVE3,USE,NX1,VALUE,DT,TFINAL,TIME,
     1THING)
      DIMENSION SAVE1(1),SAVE2(1),SAVE3(1)
      USE=0.0
      SAVE1(NX1)=VALUE
      NX2=NX1-1
      IF(NX2.EQ.0)NX2=3
      SAVE2(NX2)=VALUE
      NX3=NX2-1
      IF(NX3.EQ.0)NX3=3
      SAVE3(NX3)=VALUE
      IF((TIME.LT.(2.*DT)).OR.(TIME.GE.(TFINAL-3.*DT)))GO TO 4
      GO TO (1,2,3),NX1
    1 IF(((ABS(SAVE2(1)-SAVE2(2))).LE..001).OR.(ABS(SAVE2(2)-SAVE2(3))
     1.LE..001))GO TO 5
      IF(((SAVE2(1).LT.SAVE2(2)).AND.(SAVE2(2).GT.SAVE2(3))).OR.((SAVE2(
     11).LT.SAVE2(2)).AND.(SAVE2(2).LT.SAVE2(3))))USE=SAVE2(2)
    5 THING=SAVE2(2)
      GO TO 4
    2 IF(((ABS(SAVE3(1)-SAVE3(2))).LE..001).OR.(ABS(SAVE3(2)-SAVE3(3))
     1.LE..001))GO TO 6
      IF(((SAVE3(1).LT.SAVE3(2)).AND.(SAVE3(2).GT.SAVE3(3))).OR.((SAVE3(
     11).GT.SAVE3(2)).AND.(SAVE3(2).LT.SAVE3(3))))USE=SAVE3(2)
    6 THING=SAVE3(2)
      GO TO 4
    3 IF(((ABS(SAVE1(1)-SAVE1(2))).LE..001).OR.(ABS(SAVE1(2)-SAVE1(3))
     1.LE..001))GO TO 6
      IF(((SAVE1(1).LT.SAVE1(2)).AND.(SAVE1(2).GT.SAVE1(3))).OR.((SAVE1(
     11).GT.SAVE1(2)).AND.(SAVE1(2).LT.SAVE1(3))))USE=SAVE1(2)
    7 THING=SAVE1(2)
    4 NX1=NX1+1
      IF(NX1.EQ.4)NX1=1
      RETURN
      END
```

```
$IBFTC DISCT3
      SUBROUTINE DISCT3(XA,TABX,TABY,NY,ANS)
      DIMENSION TABX(1),TABY(1)
      CALL DISSER(XA,TABX,1,NY,2,NN)
      NNN=3
      CALL LAGRAN(XA,TABX(NN),TABY(NN),NNN,ANS)
      RETURN
      END
```

```
$IBFTC DISS
      SUBROUTINE DISSER (XA,TAB,I,NX,ID,NPX)
      DIMENSION TAB(2000)
C     DIMENSION TAB(2000)
      NPT=ID+1
      NPB=NPT/2
      NPU=NPT-NPB
      IF (NX-NPT)   10,5,10
    5 NPX=I
      RETURN
   10 NLOW=I+NPB
      NUPP=I+NX-(NPU+1)
      DO 15 II=NLOW,NUPP
      NLOC=II
      IF (TAB(II)-XA)   15,20,20
   15 CONTINUE
      NPX=NUPP-NPB+1
      RETURN
   20 NL=NLOC-NPB
      NU=NL+ID
      DO 25 JJ=NL,NU
      NDIS=JJ
      IF (TAB(JJ)-TAB(JJ+1))   25,30,25
   25 CONTINUE
      NPX=NL
      RETURN
   30 IF (TAB(NDIS)-XA)   40,35,35
   35 NPX=NDIS-ID
      RETURN
   40 NPX=NDIS+1
      RETURN
      END
```

```
$IBFTC LAGR                                                            T0000
      SUBROUTINE LAGRAN (XA,X,Y,N,ANS)                                 T0010
      DIMENSION X(200),Y(200)                                          T0020
C     DIMENSION X(200),Y(200)                                          T0030
      SUM=0.0                                                          T0040
      DO 3 I=1,N                                                       T0050
      PROD=Y(I)                                                        T0060
      DO 2 J=1,N                                                       T0070
      A=X(I)-X(J)                                                      T0080
      IF (A)    1,2,1                                                  T0090
    1 B=(XA-X(J))/A                                                    T0100
      PROD=PROD*B                                                      T0110
    2 CONTINUE                                                         T0120
    3 SUM=SUM+PROD                                                     T0130
      ANS=SUM                                                          T0140
      RETURN                                                           T0150
      END                                                              T0160
```

```
$IBFTC MORE
      DIMENSION TITLE(12),X(2000),Y1(2000),Y2(2000),Y3(2000),Y4(2000)
      REWIND 11
      READ(11) (TITLE(I),I=1,12)
      READ(11)X(1),Y1(1),Y2(1),Y3(1),Y4(1)
      Y3(1)=Y3(1)*12.+Y1(1)
      Y4(1)=Y4(1)*12.+Y1(1)
      I=2
   30 READ(11)X(I),Y1(I),Y2(I),Y3(I),Y4(I)
      IF(X(I)-5001.)10,20,20
   10 Y3(I)=Y3(I)*12.+Y1(I)
      Y4(I)=Y4(I)*12.+Y1(I)
      I=I+1
      GO TO 30
   20 NPLOT=I-1
      YM1=Y1(1)
      YM2=Y2(1)
      YM3=Y3(1)
      YM4=Y4(1)
      DO 40 K = 2 , NPLOT
      IF (Y1(K).GT.YM1) YM1 = Y1(K)
      IF (Y2(K).GT.YM2) YM2 = Y2(K)
      IF (Y3(K).GT.YM3) YM3 = Y3(K)
      IF (Y4(K).GT.YM4) YM4 = Y4(K)
   40 CONTINUE
 1000 FORMAT(1H1,(12A6))
      CALL ACCEND(X,Y1,Y2,Y3,Y4,NPLOT)
      XMAX=X(NPLOT)
       CALL APLOT (X,Y1,XMAX,YM1,TITLE,NPLOT)
      CALL BPLOT (X,Y2,XMAX,YM2,TITLE)
      CALL CPLOT (X,Y3,Y4,XMAX,YM3,YM4,TITLE,Y1)
      WRITE(6,1000)(TITLE(I),I=1,12)
      WRITE(6,1001)(X(I),Y1(I),Y2(I),Y3(I),Y4(I),I=1,NPLOT)
 1001 FORMAT(5E20.8)
      WRITE(6,1002)XMAX,YM1,YM2,YM3,YM4,NPLOT
 1002 FORMAT(///6H XMAX=F10.4,5H YM1=F10.4,5H YM2=F10.4,5H YM3=F10.4,5H
     1YM4=F10.4,2X6HNPLOT=I4)
      READ (11) (TITLE (I),I = 1,12)
      READ(11)X(1),Y1(1),Y2(1),Y3(1),Y4(1)
      I=2
      IF(X(1)-5001.)30,50,50
   50 WRITE(6,1003)(TITLE(I),I=1,12)
 1003 FORMAT(////12A6)
      RETURN
      END
```

```
$IBFTC ACCEN
      SUBROUTINE ACCEND(X,Y,A,B,C,N)
      DIMENSION X(1),Y(1),A(1),B(1),C(1)
      K=1
  101 SMALL=X(K)
      DO 100 I=K,N
      DUMY=X(I)
      SMALL=AMIN1(SMALL,DUMY)
      IF(SMALL.EQ.X(I))INDEX=I
  100 CONTINUE
      X(INDEX)=X(K)
      X(K)=SMALL
      SAVE=Y(K)
      Y(K)=Y(INDEX)
      Y(INDEX)=SAVE
      SAVEA=A(K)
      A(K)=A(INDEX)
      A(INDEX)=SAVEA
      SAVEB=B(K)
      B(K)=B(INDEX)
      B(INDEX)=SAVEB
      SAVEC=C(K)
      C(K)=C(INDEX)
      C(INDEX)=SAVEC
      K=K+1
      IF(K.EQ.N)RETURN
      GO TO 101
      END
```

```
$IBFTC APLOT
      SUBROUTINE APLOT (X,Y,XLIM,YLIM,TITLE,IPLOT)
      DIMENSION X(300),YTITLE(10),XTITLE(10)
      DIMENSION TITLE(12),Y(300),ALONGY(7)
      COMMON /ABC / ALLOW(7),ALONGX(7),NPLOT,ZERO,XMAX,IFIX
      DATA (XTITLE(I),I=1,10)/38H                          TIME (SEC.)    /
      DATA (YTITLE(I),I=1,10)/38H      SURFACE RECESSION (IN.)            /
      ZERO=0.0
      ALLOW(1)=50.
      ALLOW(2)=100.
      ALLOW(3)=250.
      ALLOW(4)=500.
      ALLOW(5)=1000.
      ALLOW(6)=2500.
      ALLOW(7)=5000.
      NPLOT=IPLOT
      DO 10 I=1,7
      II=I
      IF(XLIM- ALLOW(I)) 20,20,10
   10 CONTINUE
   30 WRITE (6,1000) XLIM,YLIM
 1000 FORMAT(///77H APLOT CANNOT BE DONE BECAUSE EITHER XLIM EXCEEDED 50
     100. OR YLIM EXCEEDED 5. /6H XLIM=E12.5,5X,6H YLIM=E12.5 // 19H WE
     2NOW GO TO BPLOT /// )
      RETURN
   20 XMAX= ALLOW(II)
      IFIX=II
      DO 40 I=1,4
      II=I
      IF(YLIM *100. -ALLOW(I) )50,50,40
   40 CONTINUE
      GO TO 30
   50 YMAX =ALLOW(II) /100.
      CALL RSTFRM
      CALL GRIDGN (123,1023,24,924,18,18,5,5)
      CALL PLOT1 (1,1,ZERO,XMAX,ZERO,YMAX,X,Y,NPLOT,1,1H/)
      ALONGX(1)=0.0
      ALONGY(1)=0.0
      DO 60 I=1,6
      CALL LABELX (ALONGX(I),1)
      CALL LABELY (ALONGY(I),1)
      ALONGX(I+1)= ALONGX(I) +.2* XMAX
   60 ALONGY(I+1)= ALONGY(I) +.2* YMAX
      CALL PRINT(200,975,12,0,38,XTITLE)
      CALL PRINT(47,200,0,12,38,YTITLE)
      CALL PRINT(123,1000,12,0,72,TITLE)
      CALL DMPBUF
      RETURN
      END
```

```
$IBFTC PPLOT
      SUBROUTINE PPLOT (X,Y,XLIM,YLIM,TITLE)
      DIMENSION X(300),Y(300),YTITLE(10),ALONGY(7),XTITLE(10)
      DIMENSION TITLE(12)
      COMMON /ABC / ALLOW(7),ALONGX(7),NPLOT,ZERO,XMAX,IFIX
      DATA (XTITLE(I),I=1,10)/38H                          TIME (SEC.)
      DATA (YTITLE(I),I=1,10)/38H          BONDLINE TEMPERATURE (R)
      ALONGY(1)=0.0
      DO 10 I=1,7
      II=I
      IF(YLIM -ALLOW(I)) 20,20,10
   10 CONTINUE
      WRITE (6,1000) YLIM
 1000 FORMAT(/// 37H PPLOT WILL NOT BE DONE BECAUSE YLIM= E12.5 ////)
      RETURN
   20 YMAX =ALLOW(II)
      CALL RSTERM
      CALL GRIDGN(123,1023,24,924,18,18,5,5 )
      CALL PLOT1 (1,1,ZERO,XMAX,ZERO,YMAX,X,Y, NPLOT,1, 1H/ )
      DO 30 I=1,6
      CALL LABELX (ALONGX(I),1)
      CALL LABELY (ALONGY(I),1)
   30 ALONGY(I+1) = ALONGY(I) + .2* YMAX
      CALL PRINT(200,975,12,0,38,XTITLE)
      CALL PRINT(47,200,0,12,38,YTITLE)
      CALL PRINT(123,1000,12,0,72,TITLE)
      CALL DMPBUF
      RETURN
      END
```

```
$IBFTC CPLOT
      SUBROUTINE CPLOT (X,Y1,Y2,XLIM,YLIM1,YLIM2,TITLE, Y)
      DIMENSION X(300),Y1(300),Y2(300),YTITLE(10),YY(2000),XTITLE(10)
      DIMENSION TITLE(12),Y(300),ALONGY(7)
      DIMENSION CURVE(1),VBUG(4),HBUG(7)
      COMMON /ABC / ALLOW(7),ALONGX(7),NPLOT,ZERO,XMAX,IFIX
      DATA (VBUG(I),I=1,4) / 100.0,50.0,20.0,10.0  /
      DATA (HBUG(I),I=1,7) / 1.0,2.0,5.0,10.0,20.0,50.0,100.0 /
      DATA (XTITLE(I),I=1,10)/38H                  TIME (SEC.)    /
      DATA (YTITLE(I),I=1,10)/38H     DISTANCE (IN.)              /
      DATA ONE/4H1060 /,TWO/4H1460 /
      DATA WON/1H1 /,TOO/1H2  /
C *** FOUR (4) CHARACTERS ARE ALLOWED FOR CURVE(1)
      CURVE(1)=ONE
      HFACTR=HBUG(IFIX)
      SYMBOL=WON
      YBIG =AMAX1 (YLIM1,YLIM2 )
      NCURVE =1
      DO 1 I=1,NPLOT
    1 YY(I)= Y1(I)
      DO 7 I=1,4
      II= I
      IF(YBIG*100. -ALLOW(I))6,6,7
    7 CONTINUE
      WRITE (6,1000) YLIM1,YLIM2
 1000 FORMAT (/// 39H CPLOT WILL NOT BE DONE BECAUSE YLIM1=F12.5,10H OR
     1YLIM2= F12.5 //// )
      RETURN
    6 YMAX =ALLOW (II)/100.
      VFACTR=VBUG(II)
      CALL RSTFRM
      CALL GRIDGN (123,1023,24,924,18,18,5,5)
      J=1
   70 DO 10 I=J,NPLOT
      II= I
      IM1 =I-1
      IF( YY(I)-Y(I) )20,10,10
   10 CONTINUE
      NOPT=NPLOT-J+1
      LL=J + NOPT/2
      IVLOC=(YMAX-YY(LL))*18.*VFACTR  +24. -4.
      IHLOC= X(LL)*18. /HFACTR  +123. -48.
      CALL PRINT(IHLOC,IVLOC, 8,0,4,CURVE)
      CALL PLOT1(1,1,ZERO,XMAX,ZERO,YMAX,X(J),YY(J),NOPT ,1,SYMBOL)
      IF (NCURVE-1 ) 90,85,90
   85 DO 86 I=1,NPLOT
   86 YY(I)=Y2(I)
      CURVE(1)=TWO
      SYMBOL=TOO
      NCURVE = 2
      J=1
      GO TO 70
   20 NPT=II-J
      LL=J +  NPT/2
      IVLOC=(YMAX-YY(LL))*18.*VFACTR  +24. -4.
      IHLOC= X(LL)*18. /HFACTR  +123. -48.
      CALL PRINT(IHLOC,IVLOC, 8,0,4,CURVE)
```

```
      CALL PLOT1(1,1,ZERO,XMAX,ZERO,YMAX,X(J),YY(J),NPT,1,SYMBOL)
      DO 50 IJ= II, NPLOT
      JJ= IJ
      IF(YY(IJ)- Y(IJ) )50,40,40
   50 CONTINUE
      IF(NCURVE-1) 90,85,90
   40 J= JJ
      GO TO 70
   90 ALONGY(1)=0.0
      DO 100 I=1,6
      CALL LABELX(ALONGX(I), 1)
      CALL LABELY(ALONGY(I),1)
  100 ALONGY(I+1)=ALONGY(I) + .2*YMAX
      CALL PRINT(200,975,12,0,38,XTITLE)
      CALL PRINT(47,200,0,12,38,YTITLE)
      CALL PRINT(123,1000,12,0,72,TITLE)
      CALL DMPBUF
      RETURN
      END
```

## APPENDIX D

## PROGRAM TERMINOLOGY

| FORTRAN | Description |
|---|---|
| A | "A" coefficient in matrix, single subscript |
| AB | "A" coefficient in matrix, double subscript |
| ABLC | specific heat of material at TABL |
| ABLK | thermal conductivity of material at TABL |
| B | "B" coefficient in matrix, single subscript |
| BB | "B" coefficient in matrix, double subscript |
| BL | Total thickness of backup structure |
| BLTEM | value of 1460 isotherm depth from previous time step |
| BTEST | test to determine mode of heat transfer out of back surface of backup materials |
| C | "C" coefficient in matrix, single subscript |
| CB | "C" coefficient in matrix, double subscript |
| CHARC | specific heat of material at TCHAR |
| CHARK | thermal conductivity of material at TCHAR |
| CP | specific heat of a node in ablation material |
| CPB | specific heat of backup material node |
| CPC | specific heat values in char specific heat table |
| CPV | specific heat values in virgin specific heat table |
| CPX | specific heat values in backup material specific heat tables |
| D | "D" coefficient in matrix, single subscript |
| DB | "D" coefficient in matrix, double subscript |
| DELTT | time step in the time step table |

| FORTRAN | Description |
|---|---|
| DMP | test used for dumping (DMP = 0 skip dump, DMP = 1.0 start dumping) |
| DRHØ | local mass flow rate of ablation gas |
| DT | time step from the time step table in hours |
| DTS | time step from time step table in seconds |
| DX | thickness of a node in the ablation material |
| DXB | thickness of a node in a backup structure material |
| DXV | variable ablation node thickness $\left(= \frac{VLV}{NP - 1}\right)$ |
| DXX | fixed ablation material node thickness $\left(= \frac{VLI}{NP - 1}\right)$ |
| EMBB | emissivity of back surface of each material in backup |
| EMC | char material emissivity |
| EMFB | emissivity of front surface of each material in backup |
| EMV | virgin material emissivity |
| EMX | emissivity of front surface of ablation material |
| END | code word for plot routine |
| ERR1, ERR2, ERR3, ERR4 | Control numbers for printing error statements when an input or calculational mistake is made |
| FBLØW | blowing efficiency in reducing convective heating |
| FCØNV | factor to correct convective heating rate for various body locations |
| FENV | emissivity - view factor product to cabin interior |
| FRAD | factor to correct radiative heating rate for various body locations |
| FTEST | test to determine mode of heat transfer into front surface of backup materials |

| FORTRAN | Description |
|---|---|
| FV | view factor for external environment |
| G | defined by FORTRAN statement |
| GAPX | gap width between backup materials |
| H | film coefficient between backup materials |
| H300 | enthalpy of air at 300° K |
| HEAD | any 72 alphanumeric characters used to identify problems being run - printed at top of first page of output |
| HEADNG | any 72 alphanumeric characters used to identify each input section |
| HENV | film coefficient to cabin environment |
| HTX | total enthalpy |
| HV | heat of degradation of virgin material |
| HW | wall enthalpy computed from enthalpy – temperature table |
| HX | enthalpy values in enthalpy table |
| IEM | test used to determine if front surface is virgin or char for using proper emissivity |
| IPRC | variable print frequency in time-step table |
| IPRCT | present print control number |
| IR | test to determine if node temperature is greater than TABL |
| IR1 | test used in determining node density at TX1 temperature |
| IR2 | test used in determining node density at TX2 temperature |
| NCASE | number of problems to be run |
| NCPB | number of points in each backup material specific heat table |
| NCPC | number of points in char specific heat temperature table |
| NCPV | number of points in virgin specific heat temperature table |
| NKC | number of points in char thermal conductivity - temperature table |

| FORTRAN | Description |
|---|---|
| NKPB | number of points in each backup material thermal conductivity table |
| NKV | number of points in virgin thermal conductivity temperature table |
| NMB | number of materials in backup structure |
| NP | number of node points in ablation material |
| NPBS | total number of node points in backup structure |
| NPF | total number of points in heat shield structure (NP + NPBS) |
| NPLØT | output plot control number |
| NPM | number of nodes per material in backup |
| NHP | number of points in enthalpy – temperature table |
| NPTT | number of points in time-step table |
| NREC | number of points in surface recession – temperature or time table |
| NTRAPT | number of points in trajectory input table |
| NXA, NXB, NXC, NXD, NXE | dummy indices for subroutine SAVE |
| QBLØCK | amount of convective heat blocked due to mass injection into boundary layer |
| QCØN | trajectory table convective heating rates |
| QCØNX | cold wall convective heat rate at present time step |
| QHW | hot wall convective heat rate without blowing |
| QIN | net heat flux into front surface |
| QLØSS | boundary condition for heat transfer to cabin interior |
| QØXID | heating rate due to combustion |

| FORTRAN | Description |
|---|---|
| QRAD | trajectory table radiative heating rates |
| QRADX | radiative heat flux at present time step |
| QUIT | code word for plot routine |
| R | thermal resistance due to conductivity between nodes in the ablation material |
| RB1 | thermal resistance due to conductivity between past and present node in backup material |
| RB2 | thermal resistance due to conductivity between present and forward node in backup material |
| RHØ | density of an ablation material node |
| RHØBX | density of individual materials in backup |
| RHØC | mature char material density |
| RHØV | virgin ablation material density |
| RHØY1 | density of node at past time step |
| RHØY2 | density of node at present time step |
| S | thermal capacity of a node in the ablation material |
| SDØT | surface recession rate |
| SAVEIT | depth of 1060 isotherm at any given time |
| SAVEXX | time corresponding to maximum depth of 1460 isotherm |
| SAVX | time corresponding to maximum depth of 1060 isotherm |
| SAVY1 | surface recession depth at maximum 1060 isotherm depth |
| SAVY2 | bondline temperature at maximum 1060 isotherm depth |
| SAVY3 | term that will contain maximum depth of 1060 isotherm |
| SAVY4 | depth of 1460 isotherm at maximum 1060 isotherm depth |
| SAVY1X | surface recession depth at maximum 1460 isotherm depth |
| SAVY2X | bondline temperature at maximum 1460 isotherm depth |

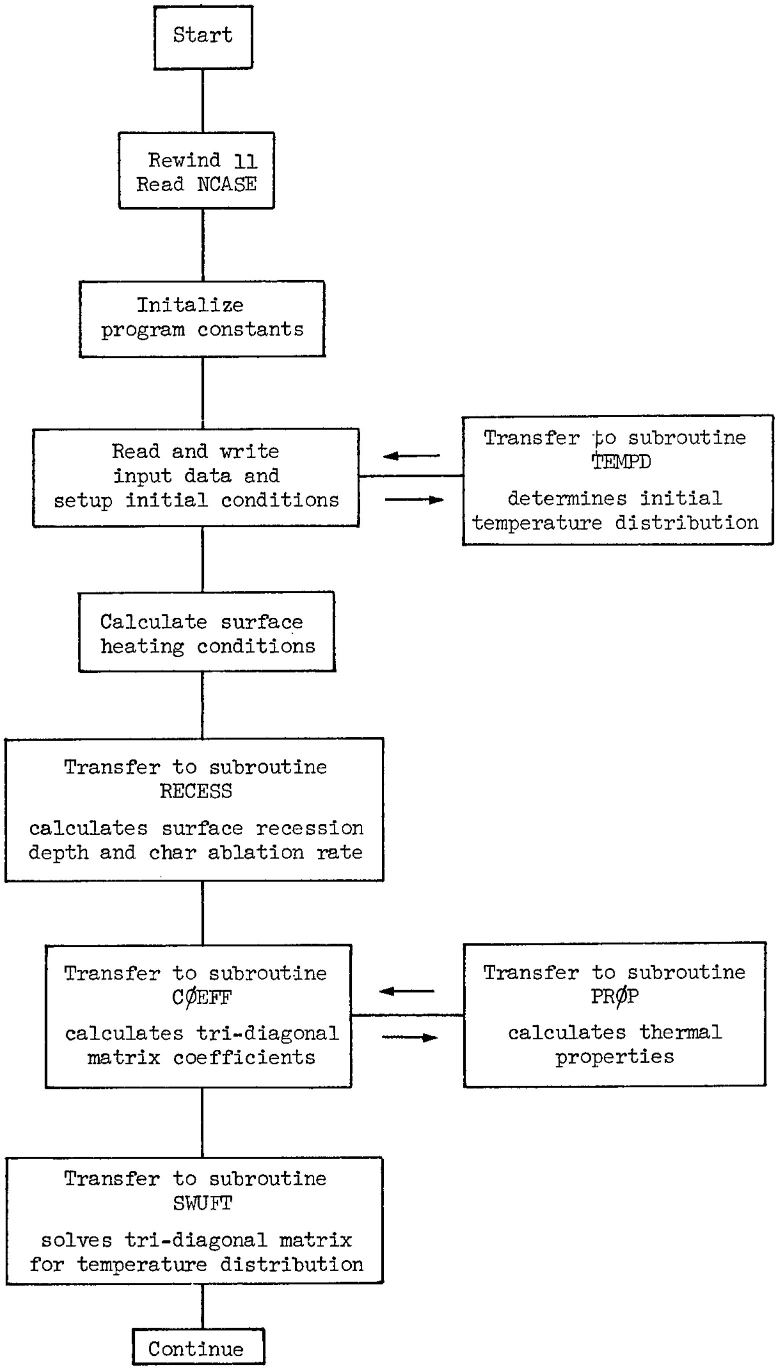
| FORTRAN | Description |
|---|---|
| SAVY3X | depth of 1060 isotherm at maximum 1460 isotherm depth |
| SAVY4X | term that will contain maximum depth of 1460 isotherm |
| SR | surface recession values in surface recession table |
| T | present time |
| TABL | temperature at which ablation starts |
| TCHAR | temperature at which ablation stops |
| TCP | temperature values in backup material specific heat tables |
| TCPC | temperature values in char specific heat table |
| TCPV | temperature values in virgin specific heat table |
| TEMDI | arbitrary initial temperature distribution values |
| TEMPI | constant initial temperature distribution value |
| TENV | interior cabin temperature |
| TEST2 | test to determine proper heat shield initial temperature distribution |
| TDMP | time to start dumping or printing information used in checkout of program (sets DMP = 1.0) |
| TIME | trajectory table time values |
| TINT | starting time of problem |
| TITLE | control card used for reading in new data for successive problems |
| TKC | temperature values in char thermal conductivity table |
| TKV | temperature values in virgin thermal conductivity table |
| TL | total thickness of heat shield structure (VL + BL) |
| TLIM | time limit of problem |
| TREC | surface temperature or time at which char removal is to start |
| TS | temperature or time values in surface recession table |
| TTABLE | time values in time-step table |

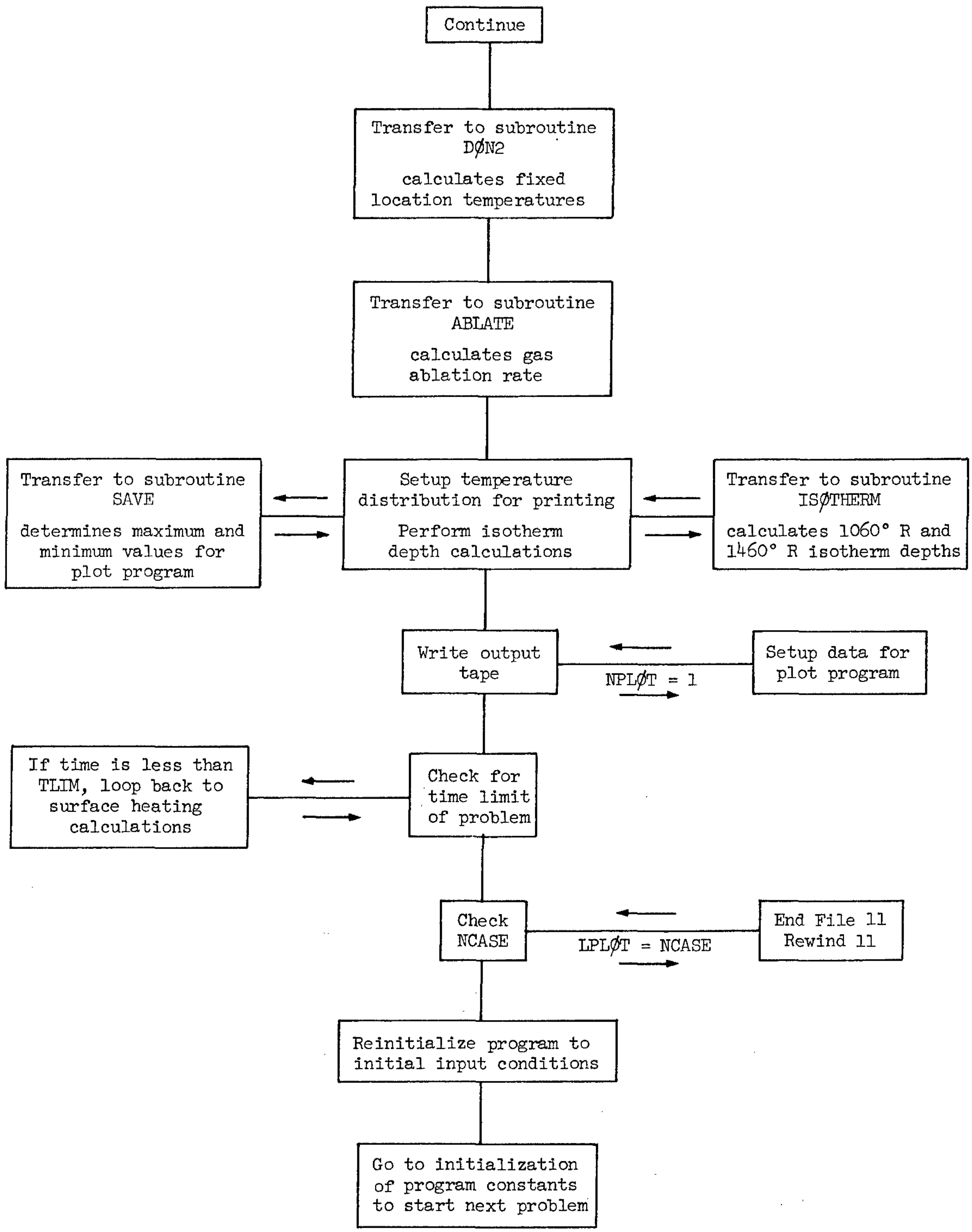
| FORTRAN | Description |
|---|---|
| TTUL | equals TUL if VPT = 0 or equals TX2 if VPT = 1 - used in computing char properties |
| TUL | maximum value of TX1 and TX2 |
| TUL1 | maximum TX1 values - used in computing gas ablation rate |
| TUL2 | maximum TX2 values - used in computing gas ablation rate |
| TV | sink temperature of external environment |
| TW | temperature values in enthalpy table |
| TX1 | temperature of nodes at past time step |
| TX2 | temperature of nodes at present time step |
| TX2C | temperature at fixed locations in ablation material as defined by XC |
| TX2T | temporary storage of TX2 temperatures for computing thermal properties |
| TXK | temperature values in backup material thermal conductivity tables |
| TXØ | initial temperature at front surface of heat shield for computing linear temperature gradient |
| TY | temperature distribution at forward time step |
| VEL | trajectory table velocity values |
| VELX | trajectory velocity at present time step |
| VL | initial virgin material thickness |
| VLI | initial ablation material thickness |
| VLTEM | value of 1060 isotherm depth from previous time step |
| VLV | variable ablation material thickness |
| VPT | test to determine if properties are irreversible with temperature |
| WEKEEP | depth of 1460 isotherm at any time |
| XBM | thickness of individual materials in backup |
| XC | fixed location of nodes in the ablation material |
| XI | node number |

| FORTRAN | Description |
|---|---|
| XIDNT | any 72 alphanumeric characters to identify each material |
| XK | thermal conductivity values in backup material thermal conductivity table |
| XKB | thermal conductivity of backup material node |
| XKC | thermal conductivity in char thermal conductivity table |
| XKV | thermal conductivity value in virgin thermal conductivity table |
| XLØST | amount of solid ablation material lost in a time step due to surface movement |
| XLSTI | distance from original surface to present front surface location, inches |
| XLSTV | distance from original surface to present front surface location, feet |
| XMDC | mass loss rate of char |
| XMDG | mass gas ablation rate due to pyrolysis of virgin material |
| XMDØ | mass flux rate of oxygen to surface |
| XMDT | total ablation rate |
| XNP | number of nodes in ablation material |
| XNPM | number of nodes per backup material |
| XPLØT | time to be written on tape and plotted |
| XV | location of nodes in variable ablation material thickness |
| YK | thermal conductivity of a node in ablation material |
| YPLØT1 | recession depth to be written on tape and plotted |
| YPLØT2 | bondline temperature to be written on tape and plotted |
| YPLØT3 | 1060 isotherm depth to be written on tape and plotted |
| YPLØT4 | 1460 isotherm depth to be written on tape and plotted |
| ZZZ | ratio to determine when the limiting value of heat blockage has been reached |

APPENDIX E

GENERAL FLOW CHART





Continue
Transfer to subroutine DØN2
calculates fixed location temperatures
Transfer to subroutine ABLATE
calculates gas ablation rate
Transfer to subroutine SAVE
determines maximum and minimum values for plot program
Setup temperature distribution for printing
Perform isotherm depth calculations
Transfer to subroutine ISØTHERM
calculates 1060° R and 1460° R isotherm depths
Write output tape
NPLØT = 1
Setup data for plot program
If time is less than TLIM, loop back to surface heating calculations
Check for time limit of problem
Check NCASE
LPLØT = NCASE
End File 11
Rewind 11
Reinitialize program to initial input conditions
Go to initialization of program constants to start next problem

TABLE I.- SAMPLE PROBLEM INPUT

(a) Coding sheet

STATEMENT NUMBER | CONTINUATION | FORTRAN STATEMENT | SEQUENCE

LOCATION | OPERATION | VARIABLE FIELD | COMMENTS

```
    1
     TYPICAL CHARRING ABLATOR - TEST CASE - 4/6/65   DONALD M. CURRY

+600.0   +00 +0.0     +00   2      1
+0.0     +00 +0.1     +00   100
+600.0   +00 +0.1     +00   100

+1.0     +00 +1.0     +00

    TYPICAL CHARRING ABLATION MATERIAL PROPERTIES
+1060.0 +00 +1460.0 +00 +0.0     +00 +34.0   +00 +20.0   +00 +0.0    +00
+0.65    +00 +0.75   +00 +129.06+00 +1.5    +00 +250.0  +00 +0.0    +00
+1.0     +00 +0.0    +00 +0.12    +00 +0.43   +00 +0.070  +00 +0.43   +00
  31     2   2       9   2        2
+1460.0 +00 +0.12   +00 +1.0     +04 +0.12   +00
+1460.0 +00 +0.43   +00 +1.0     +04 +0.43   +00
+360.0   +00 +0.065  +00 +460.0   +00 +0.065  +00 +560.0  +00 +0.0655 +00
+660.0   +00 +0.066  +00 +760.0   +00 +0.0672 +00 +860.0  +00 +0.0684 +00
+960.0   +00 +0.069  +00 +1060.0  +00 +0.070  +00 +1160.0 +00 +0.070  +00
+360.0   +00 +0.43   +00 +1100.0  +00 +0.43   +00
+0.0     +00 +9.0    -04 +600.0   +00 +9.0    -04

     NO TRAJECTORY - Q=95 BTU/SEC-SQFT
    2
+0.0     +00 +95.0   +00 +0.0     +00 +2.925  +04
```

MSC Form 244 (Apr 1962)

NOTE: WRITE NUMBERS 10, LETTERS IØUGZC, SYMBOLS /.,*

TABLE I.- SAMPLE PROBLEM INPUT - Continued

(a) Coding sheet

FORTRAN STATEMENT

| LOCATION (cols. 1–7) | OPERATION / VARIABLE FIELD / COMMENTS (cols. 8–72) | SEQUENCE |
|---|---|---|
| +600.0 | +00 +95.0 +00 +0.0 +00 +2.925 +04 | |
| | | |
| 1 | 3 +0.1 +00 | |
| +3.0 | +00 | |
| 9 | 2 | |
| BACKUP MATERIAL 0.1 INCHES THICK | | |
| +360.0 | +00 +0.065 +00 +460.0 +00 +0.065 +00 +560.0 | |
| +660.0 | +00 +0.066 +00 +760.0 +00 +0.0672 +00 +860.0 +00 +0.0655 +00 | |
| +960.0 | +00 +0.069 +00 +1060.0 +00 +0.07 +00 +1160.0 +00 +0.0684 +00 | |
| +360.0 | +00 +0.43 +00 +1100.0 +00 +0.43 +00 +0.07 +00 | |
| +34.0 | +00 +0.1 +00 +0.9 +00 +0.9 +00 | |
| +0.0 | +00 +0.0 +00 +0.0 +00 +0.0 +00 | |
| | | |
| HEAT TRANSFER TO CABIN ENVIRONMENT - HENV=0.0 | | |
| +560.0 | +00 +0.0 +00 +0.0 +00 +0.0 +00 | |
| | | |
| INITIAL TEMPERATURE IS CONSTANT | | |
| +0.0 | +00 +530.0 +00 +530.0 +00 | |
| | | |
| 42 | | |
| +0.0 | +00 +0.0 +00 +342.9 +00 +1400.0 +00 +449.7 +00 +1800.0 +00 | |
| +617.2 | +00 +2400.0 +00 +791.0 +00 +3000.0 +00 +918.0 +00 +3600.0 +00 | |
| +1113.0 | +00 +4006.0 +00 +1200.0 +00 +4224.0 +00 +1300.0 +00 +4486.0 +00 | |
| +1400.0 | +00 +4723.0 +00 +1500.0 +00 +4936.0 +00 +1600.0 +00 +5127.0 +00 | |
| +1700.0 | +00 +5299.0 +00 +1800.0 +00 +5454.0 +00 +1900.0 +00 +5596.0 +00 | |

MSC Form 244 (Apr 1962)

NOTE: WRITE NUMBERS 10, LETTERS IØUGZC, SYMBOLS /.,*

3537-64

TABLE I.- SAMPLE PROBLEM INPUT - Concluded

(a) Coding sheet

FORTRAN STATEMENT

STATEMENT NUMBER — CONTINUATION — LOCATION — OPERATION — VARIABLE FIELD — COMMENTS — SEQUENCE

```
+2000.0 +00 +5728.0 +00 +2100.0 +00 +5851.0 +00 +2200.0 +00 +5968.0 +00
+2300.0 +00 +6078.0 +00 +2400.0 +00 +6186.0 +00 +2500.0 +00 +6291.0 +00
+2600.0 +00 +6395.0 +00 +2700.0 +00 +6497.0 +00 +2800.0 +00 +6597.0 +00
+2900.0 +00 +6699.0 +00 +3000.0 +00 +6805.0 +00 +3100.0 +00 +6918.0 +00
+3200.0 +00 +7050.0 +00 +3300.0 +00 +7175.0 +00 +3400.0 +00 +7350.0 +00
+3500.0 +00 +7480.0 +00 +3600.0 +00 +7630.0 +00 +3700.0 +00 +7800.0 +00
+3800.0 +00 +7970.0 +00 +3900.0 +00 +8120.0 +00 +4000.0 +00 +8300.0 +00
+4100.0 +00 +8500.0 +00 +4200.0 +00 +8700.0 +00 +4300.0 +00 +8850.0 +00
+4400.0 +00 +9000.0 +00 +4500.0 +00 +9150.0 +00 +4600.0 +00 +9270.0 +00
```

MSC Form 244 (Apr 1962)

NOTE: WRITE NUMBERS 10, LETTERS IØUGZC, SYMBOLS /.,*

3537-64

TABLE I.- SAMPLE PROBLEM INPUT

(b) Fortran data card listing

```
  1
   TYPICAL CHARRING ABLATOR - TEST CASE - 4/6/65     DONALD M. CURRY

+600.0   +00 +0.0     +00      2     1
+0.0     +00 +0.1     +00    100
+600.0   +00 +0.1     +00    100

+1.0     +00 +1.0     +00

  TYPICAL CHARRING ABLATION MATERIAL PROPERTIES
+1060.0 +00 +1460.0 +00 +0.0     +00 +34.0    +00 +20.0    +00 +0.00    +00
+0.65    +00 +0.75    +00 +129.06 +00 +1.50    +00 +250.0   +00 +0.0     +00
+1.0     +00 +0.0     +00 +0.12    +00 +0.43    +00 +0.070   +00 +0.43    +00
  31     2    2    9     2    2
+1460.0 +00 +0.12    +00 +1.0     +04 +0.12    +00
+1460.0 +00 +0.43    +00 +1.0     +04 +0.43    +00
+360.0   +00 +0.065   +00 +460.0   +00 +0.065   +00 +560.0   +00 +0.0655 +00
+660.0   +00 +0.066   +00 +760.0   +00 +0.0672 +00 +860.0   +00 +0.0684 +00
+960.0   +00 +0.069   +00 +1060.0 +00 +0.070   +00 +1160.0 +00 +0.070   +00
+360.00 +00 +0.43    +00 +1100.0 +00 +0.43    +00
+0.0     +00 +9.0     -04 +600.0   +00 +9.0     -04

  NO TRAJECTORY - Q=95 BTU/SEC-SQFT
   2
+0.0     +00 +95.0    +00 +0.0     +00 +2.925   +04
+600.0   +00 +95.0    +00 +0.0     +00 +2.925   +04

   1     3    +0.1     +00
+3.0     +00
   9     2
  BACKUP MATERIAL                     0.1 INCHES THICK
+360.0   +00 +0.065   +00 +460.0   +00 +0.065   +00 +560.0   +00 +0.0655 +00
+660.0   +00 +0.066   +00 +760.0   +00 +0.0672 +00 +860.0   +00 +0.0684 +00
+960.0   +00 +0.069   +00 +1060.0 +00 +0.07    +00 +1160.0 +00 +0.07    +00
+360.00 +00 +0.43    +00 +1100.0 +00 +0.43    +00
+34.0    +00 +0.1     +00 +0.9     +00 +0.9     +00
+0.0     +00 +0.0     +00 +0.0     +00 +0.0     +00

 HEAT TRANSFER TO CABIN ENVIRONMENT - HENV=0.0
+560.0   +00 +0.0     +00 +0.0     +00 +0.0     +00

 INITIAL TEMPERATURE IS CONSTANT
+0.0     +00 +530.0   +00 +530.0   +00

  42
+0.0     +00 +0.0     +00 +342.9   +00 +1400.0 +00 +449.7   +00 +1800.0 +00
+617.2   +00 +2400.0 +00 +791.0   +00 +3000.0 +00 +978.0   +00 +3600.0 +00
+1113.0 +00 +4000.0 +00 +1200.0 +00 +4224.0 +00 +1300.0 +00 +4486.0 +00
+1400.0 +00 +4725.0 +00 +1500.0 +00 +4936.0 +00 +1600.0 +00 +5127.0 +00
+1700.0 +00 +5299.0 +00 +1800.0 +00 +5454.0 +00 +1900.0 +00 +5596.0 +00
+2000.0 +00 +5728.0 +00 +2100.0 +00 +5851.0 +00 +2200.0 +00 +5968.0 +00
+2300.0 +00 +6078.0 +00 +2400.0 +00 +6186.0 +00 +2500.0 +00 +6291.0 +00
+2600.0 +00 +6395.0 +00 +2700.0 +00 +6497.0 +00 +2800.0 +00 +6597.0 +00
+2900.0 +00 +6699.0 +00 +3000.0 +00 +6805.0 +00 +3100.0 +00 +6918.0 +00
```

TABLE I - SAMPLE PROBLEM INPUT - Concluded

(b) Fortran data card listing

```
+3200.0   +00+7050.0   +00+3300.0   +00+7175.0   +00+3400.0   +00+7350.0   +00
+3500.0   +00+7480.0   +00+3600.0   +00+7630.0   +00+3700.0   +00+7800.0   +00
+3800.0   +00+7970.0   +00+3900.0   +00+8120.0   +00+4000.0   +00+8300.0   +00
+4100.0   +00+8600.0   +00+4200.0   +00+8700.0   +00+4300.0   +00+8850.0   +00
+4400.0   +00+9000.0   +00+4500.0   +00+9150.0   +00+4600.0   +00+9270.00  +00
```

TABLE II.- SAMPLE PROBLEM OUTPUT

TYPICAL CHARRING ABLATOR - TEST CASE - 4/6/65 DONALD M. CURRY

INPUT DATA.

TIME LIMIT=6.0000E 02 INITIAL TIME=0. NPTT= 2

| TIME | TIME STEP | PRINT CONTROL |
|---|---|---|
| 0. | 1.0000E-01 | 100 |
| 6.0000E 02 | 1.0000E-01 | 100 |

FCONV= 1.00000E 00 FRAD= 1.00000E 00

TYPICAL CHARRING ABLATION MATERIAL PROPERTIES

TABL= 1.06000E 03 TCHAR= 1.46000E 03 TREC= 0. RHOV= 3.40000E 01 RHOC= 2.00000E 01
FBLOW= 0. EMV= 6.50000E-01 EMC= 7.50000E-01 H300= 1.29060E 02 VL= 1.50000E 00
HV= 2.50000E 02 VPT= 0. FV= 1.00000E 00 TV= 0. CHARK= 1.20000E-01
CHARC= 4.30000E-01 ABLK= 7.00000E-02 ABLC= 4.30000E-01

NP= 31 NKC= 2 NCPC= 2 NKV= 9 NCPV= 2 NREC= 2

VIRGIN MATERIAL

| TEMPERATURE | THERMAL CONDUCTIVITY | TEMPERATURE | SPECIFIC HEAT |
|---|---|---|---|
| 3.60000E 02 | 6.50000E-02 | 3.60000E 02 | 4.30000E-01 |
| 4.60000E 02 | 6.50000E-02 | 1.10000E 03 | 4.30000E-01 |
| 5.60000E 02 | 6.55000E-02 | | |
| 6.60000E 02 | 6.60000E-02 | | |
| 7.60000E 02 | 6.72000E-02 | | |
| 8.60000E 02 | 6.84000E-02 | | |
| 9.60000E 02 | 6.90000E-02 | | |
| 1.06000E 03 | 7.00000E-02 | | |
| 1.16000E 03 | 7.00000E-02 | | |

CHAR MATERIAL

| TEMPERATURE | THERMAL CONDUCTIVITY | TEMPERATURE | SPECIFIC HEAT |
|---|---|---|---|
| 1.46000E 03 | 1.20000E-01 | 1.46000E 03 | 4.30000E-01 |
| 1.00000E 04 | 1.20000E-01 | 1.00000E 04 | 4.30000E-01 |

SURFACE RECESSION TABLE

| TIME | SR - IN/SEC |
|---|---|
| 0. | 9.00000E-04 |
| 6.00000E 02 | 9.00000E-04 |

NO TRAJECTORY - Q=95 BTU/SEC-SQFT

NO. OF TRAJECTORY POINTS = 2

TABLE II.- SAMPLE PROBLEM OUTPUT - Continued

| TIME | Q CONVECTIVE | Q RADIATIVE | VELOCITY |
|---|---|---|---|
| 0. | 9.50000E 01 | 0. | 2.92500E 04 |
| 6.00000E 02 | 9.50000E 01 | 0. | 2.92500E 04 |

PROPERTIES OF BACKUP STRUCTURE

NO. OF MATERIALS IN BACK-UP SHIELD= 1
TOTAL NUMBER OF NODES IN BACK-UP SHIELD= 3
THICKNESS OF BACK-UP SHIELD= 1.00000E-01

BACKUP MATERIAL 0.1 INCHES THICK

| TEMPERATURE | THERMAL CONDUCTIVITY |
|---|---|
| 3.60000E 02 | 6.50000E-02 |
| 4.60000E 02 | 6.50000E-02 |
| 5.60000E 02 | 6.55000E-02 |
| 6.60000E 02 | 6.60000E-02 |
| 7.60000E 02 | 6.72000E-02 |
| 8.60000E 02 | 6.84000E-02 |
| 9.60000E 02 | 6.90000E-02 |
| 1.06000E 03 | 7.00000E-02 |
| 1.16000E 03 | 7.00000E-02 |

| TEMPERATURE | SPECIFIC HEAT |
|---|---|
| 3.60000E 02 | 4.30000E-01 |
| 1.10000E 03 | 4.30000E-01 |

| MATERIAL | DENSITY | THICKNESS | EMISSIVITY FRONT | EMISSIVITY BACK | NODES/MATERIAL |
|---|---|---|---|---|---|
| 1 | 3.4000E 01 | 1.0000E-01 | 9.0000E-01 | 9.0000E-01 | 3.0000E 00 |

ADDITIONAL DATA FOR INDIVIDUAL MATERIALS IN BACKUP STRUCTURE

| MATERIAL | FILM COEFFICIENT | GAP THICKNESS | FTEST | BTEST |
|---|---|---|---|---|
| 1 | 0. | 0. | 0. | 0. |

HEAT TRANSFER TO CABIN ENVIRONMENT - HENV=0.0

TEMPERATURE= 5.60000E 02 FILM COEFFICIENT= 0. VIEW FACTOR= 0. Q LOST= 0.

INITIAL TEMPERATURE IS CONSTANT

TEMPERATURE DISTRIBUTION IN HEAT SHIELD IS UNIFORM AND EQUAL TO 5.3000E 02

TABLE II.- SAMPLE PROBLEM OUTPUT - Concluded

OUTPUT DATA.

TIME= 9.90000E 00  QCONVECTIVE= 9.50000E 01  QRADIATIVE= 0.  VELOCITY= 2.92500E 04
GAS ABLATION RATE= 0.  CHAR ABLATION RATE= 5.40000E 00  TOTAL ABLATION RATE= 5.40000E 00
RECESSION DEPTH= 9.00000E-03  QHOT WALL= 8.99282E 01

TEMPERATURE DISTRIBUTION IN HEAT SHIELD AT THE END OF THE TIME STEP, T= 1.00000E 01 SECONDS

TEMPERATURE DISTRIBUTION IN THE ABLATING MATERIAL

| | | | | | |
|---|---|---|---|---|---|
| 3.79022E 03 | 2.33046E 03 | 1.06300E 03 | 6.38075E 02 | 5.47600E 02 | 5.32434E 02 |
| 5.30289E 02 | 5.30030E 02 | 5.30002E 02 | 5.30000E 02 | 5.30000E 02 | 5.30000E 02 |
| 5.30000E 02 | 5.30000E 02 | 5.29999E 02 | 5.30000E 02 | 5.30000E 02 | 5.30000E 02 |
| 5.30000E 02 | 5.30000E 02 | 5.30000E 02 | 5.30000E 02 | 5.30000E 02 | 5.30000E 02 |
| 5.30000E 02 | 5.30000E 02 | 5.30000E 02 | 5.29999E 02 | 5.30000E 02 | 5.30000E 02 |
| 5.29999E 02 | | | | | |

TEMPERATURE DISTRIBUTION IN THE BACK-UP STRUCTURE

| | | |
|---|---|---|
| 5.29999E 02 | 5.30000E 02 | 5.30000E 02 |

TIME= 1.99000E 01  QCONVECTIVE= 9.50000E 01  QRADIATIVE= 0.  VELOCITY= 2.92500E 04
GAS ABLATION RATE= 2.90720E 01  CHAR ABLATION RATE= 5.40000E 00  TOTAL ABLATION RATE= 3.44720E 01
RECESSION DEPTH= 1.80000E-02  QHOT WALL= 8.99173E 01

TEMPERATURE DISTRIBUTION IN HEAT SHIELD AT THE END OF THE TIME STEP, T= 2.00000E 01 SECONDS

TEMPERATURE DISTRIBUTION IN THE ABLATING MATERIAL

| | | | | | |
|---|---|---|---|---|---|
| 3.80935E 03 | 2.87678E 03 | 1.64575E 03 | 9.77202E 02 | 6.72698E 02 | 5.66204E 02 |
| 5.37857E 02 | 5.31496E 02 | 5.30254E 02 | 5.30038E 02 | 5.30005E 02 | 5.30000E 02 |
| 5.29999E 02 | 5.29999E 02 | 5.29999E 02 | 5.29999E 02 | 5.29999E 02 | 5.29999E 02 |
| 5.29999E 02 | 5.29999E 02 | 5.29999E 02 | 5.29999E 02 | 5.29999E 02 | 5.29999E 02 |
| 5.29999E 02 | 5.29999E 02 | 5.29999E 02 | 5.29999E 02 | 5.29999E 02 | 5.29999E 02 |
| 5.29999E 02 | | | | | |

TEMPERATURE DISTRIBUTION IN THE BACK-UP STRUCTURE

| | | |
|---|---|---|
| 5.29999E 02 | 5.29999E 02 | 5.29999E 02 |

TIME= 2.99000E 01  QCONVECTIVE= 9.50000E 01  QRADIATIVE= 0.  VELOCITY= 2.92500E 04
GAS ABLATION RATE= 1.25330E 01  CHAR ABLATION RATE= 5.40000E 00  TOTAL ABLATION RATE= 1.79330E 01
RECESSION DEPTH= 2.70000E-02  QHOT WALL= 8.98427E 01

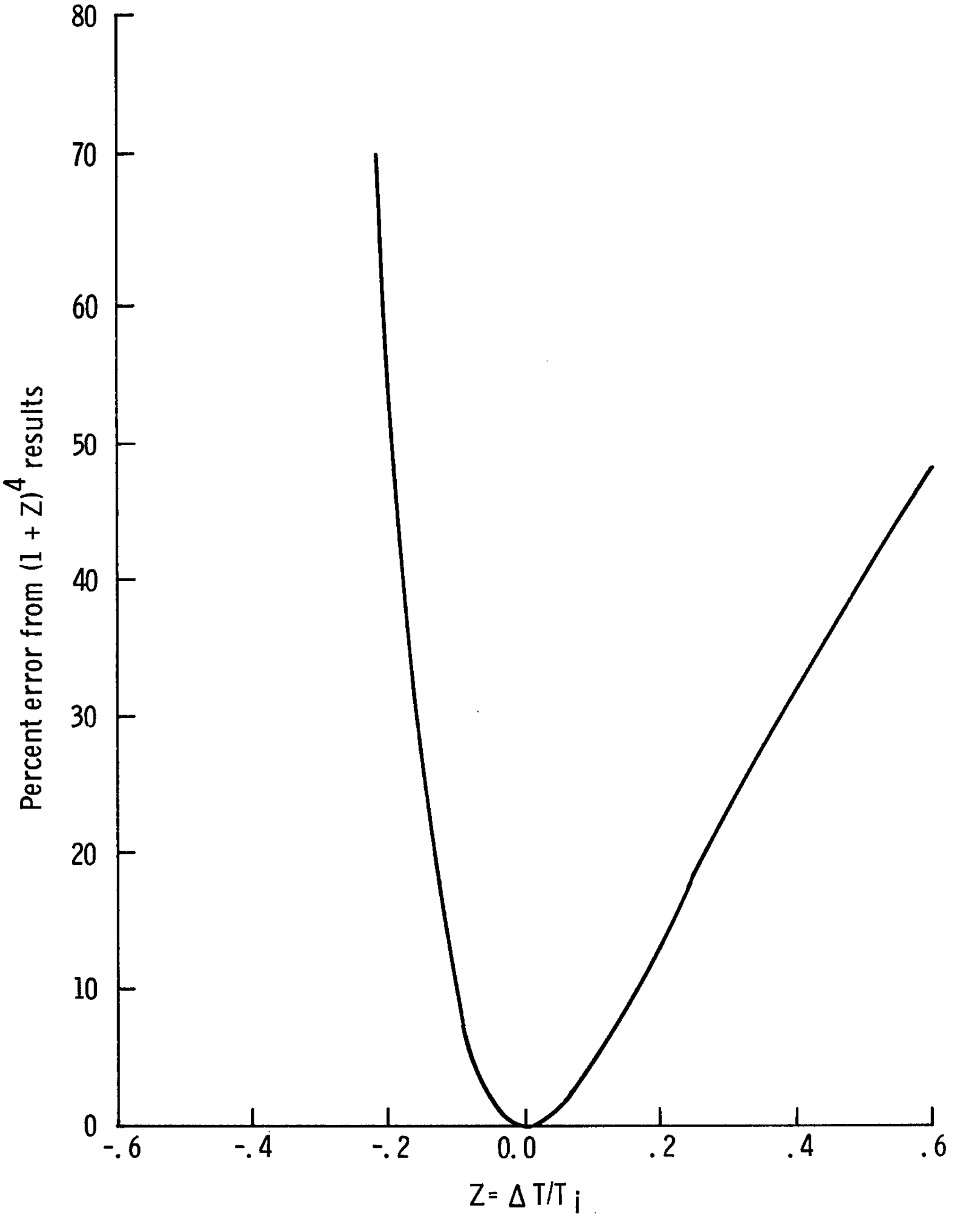



Figure 1. - Radiation temperature approximation error.

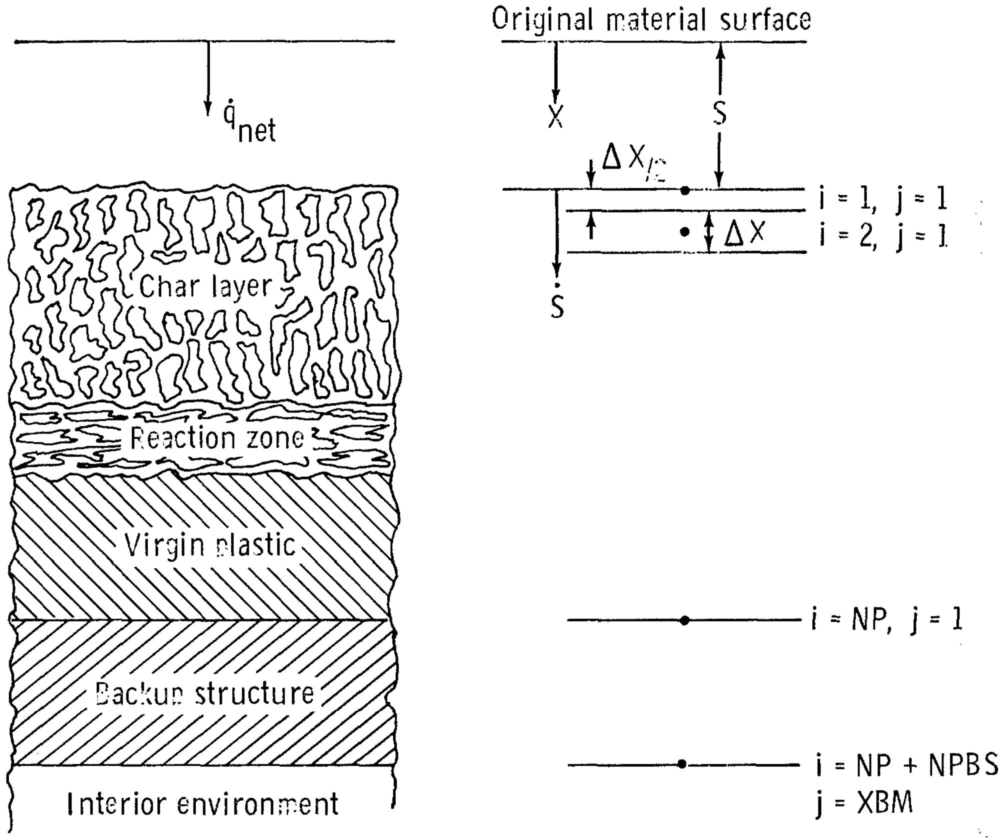



Figure 2. - Schematic diagram of charring ablator thermal protection system.

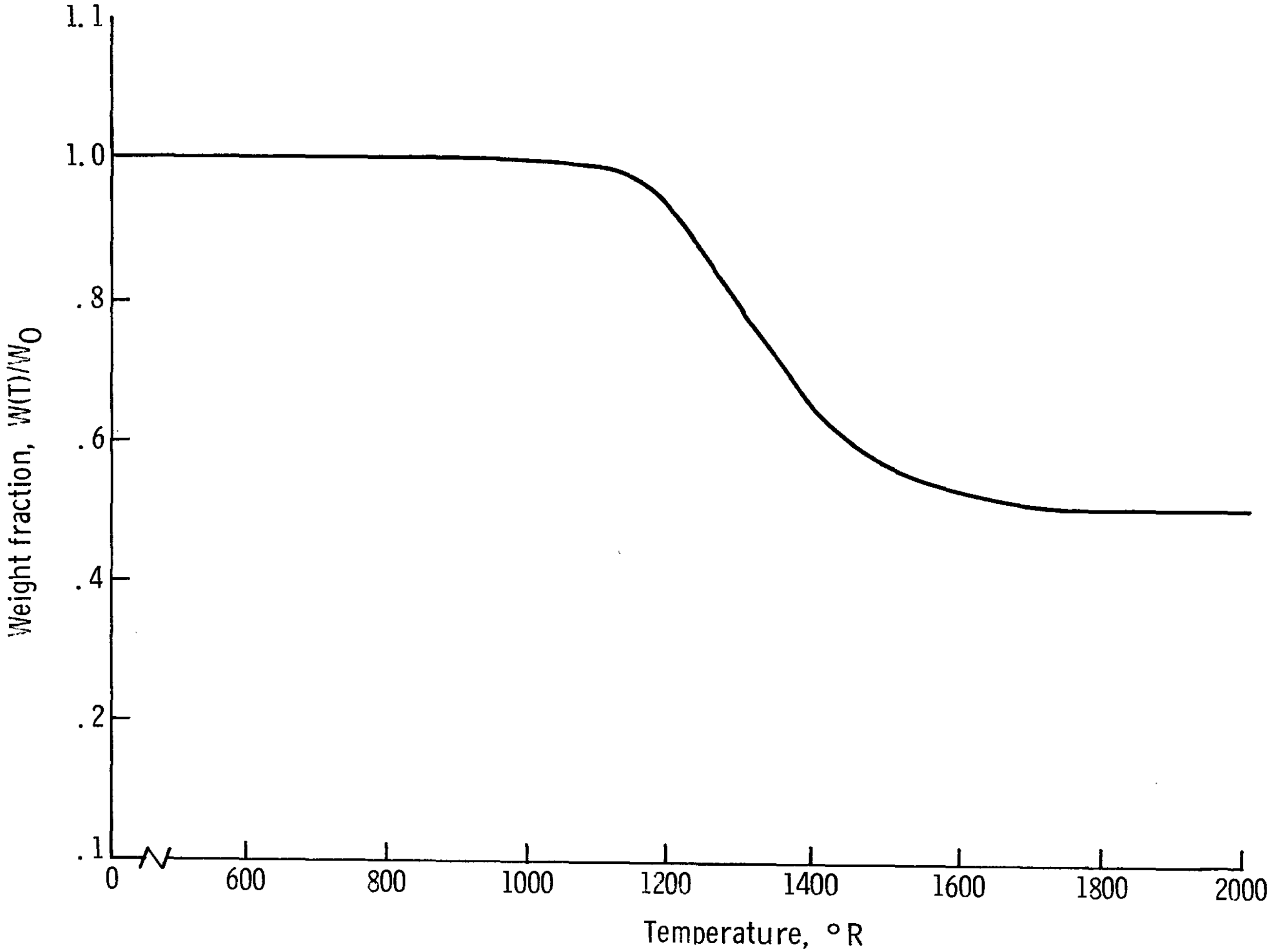



Figure 3. - Thermogravimetric data for typical charring ablation material.

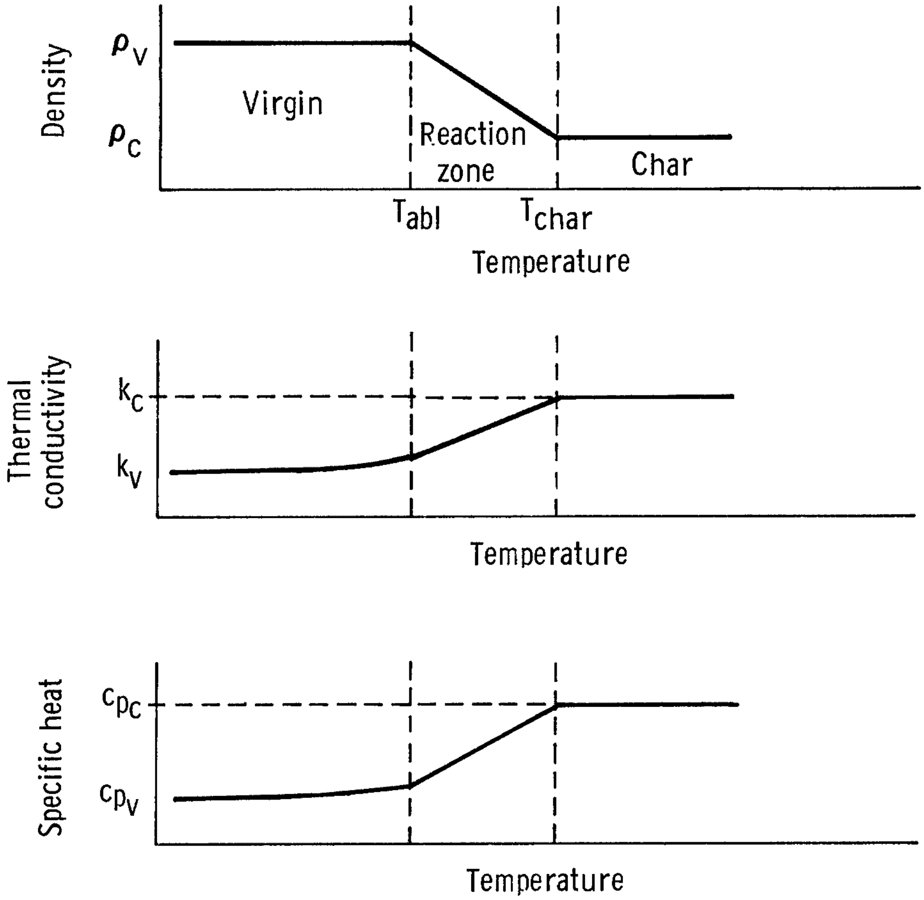



Figure 4. - Charring material property variation used as input to STAB II.

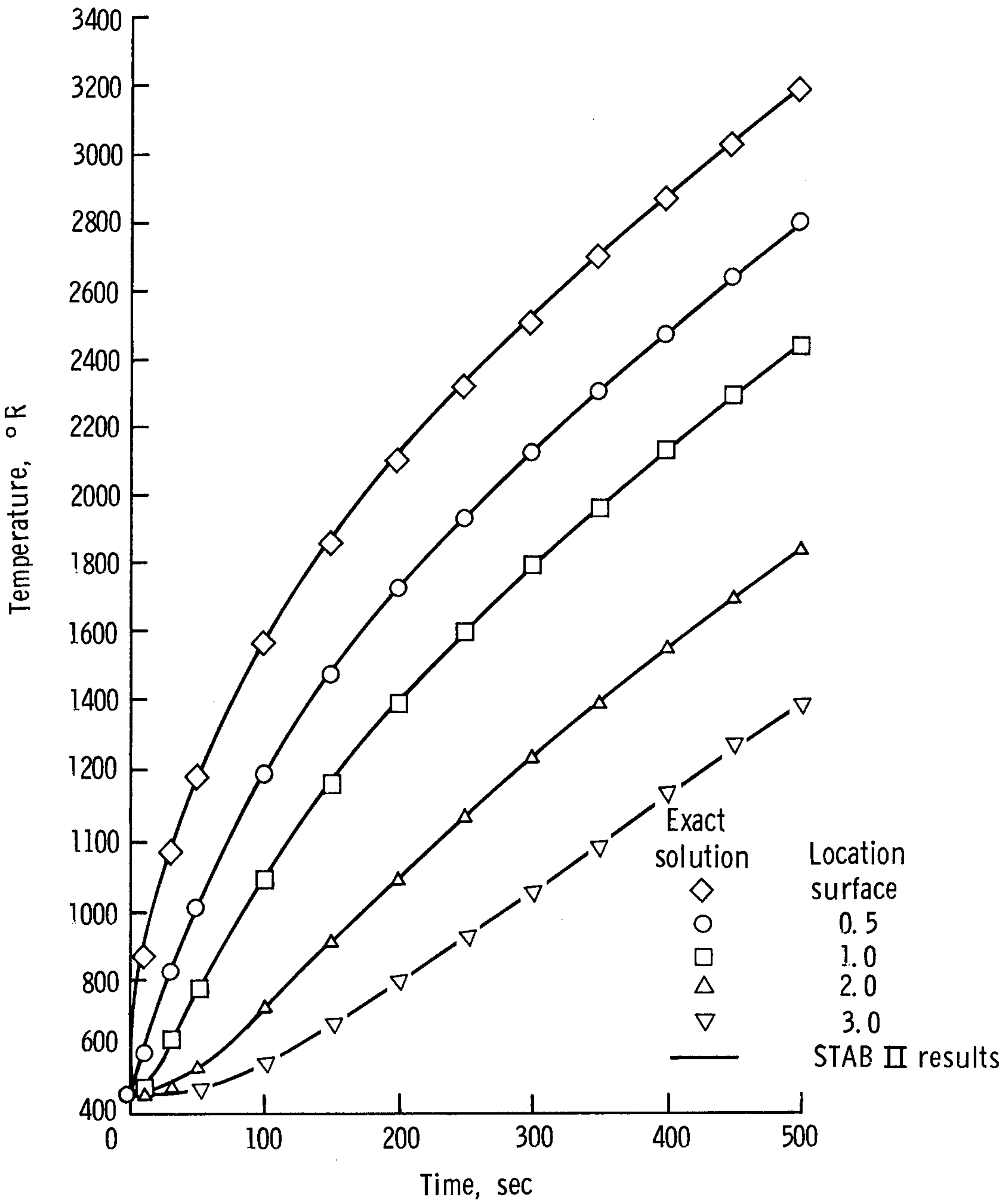



Figure 5. - Comparison of temperature histories for nonablating steel slab (pure conduction)

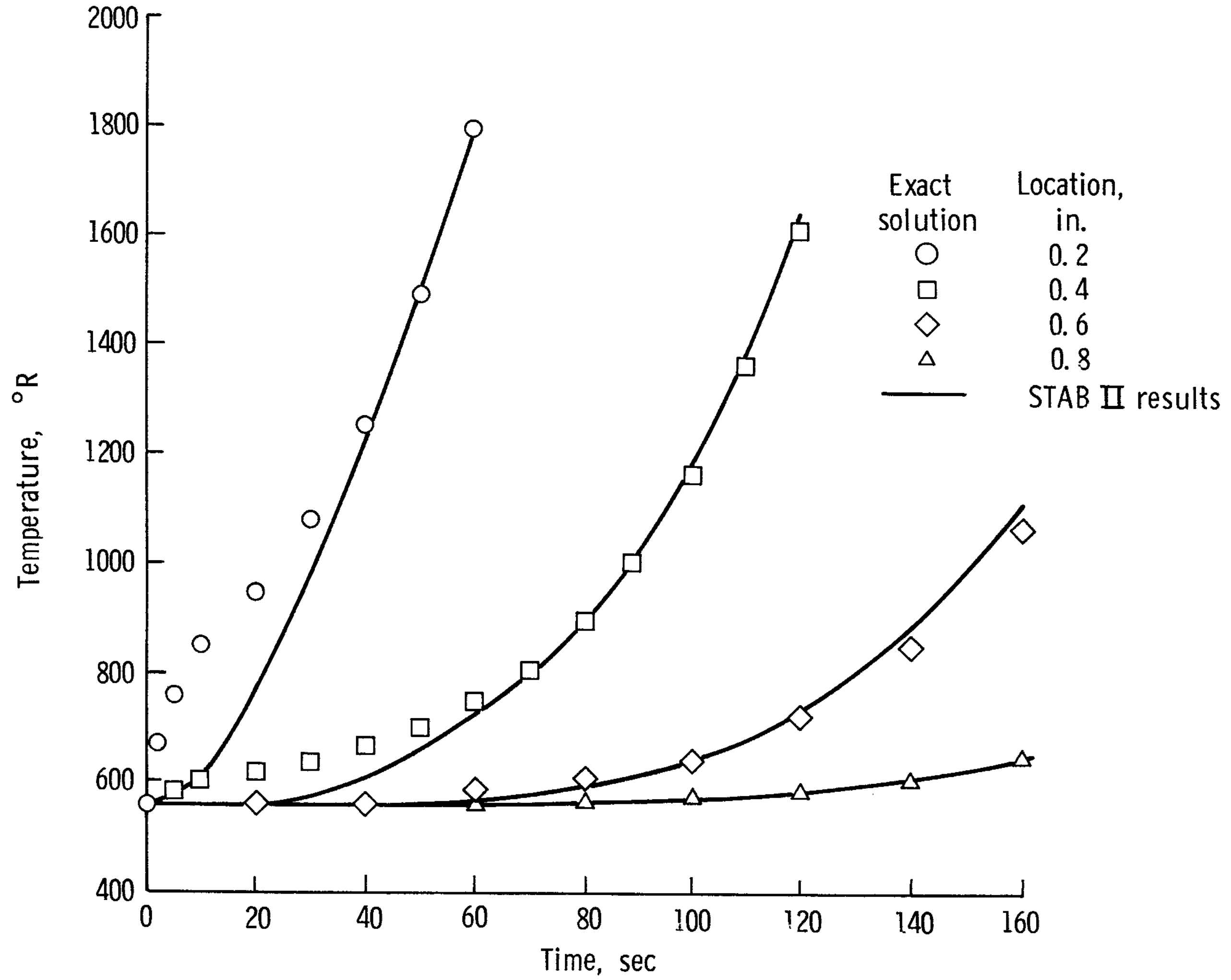



Figure 6. - Comparison of temperature histories for moving boundary model.

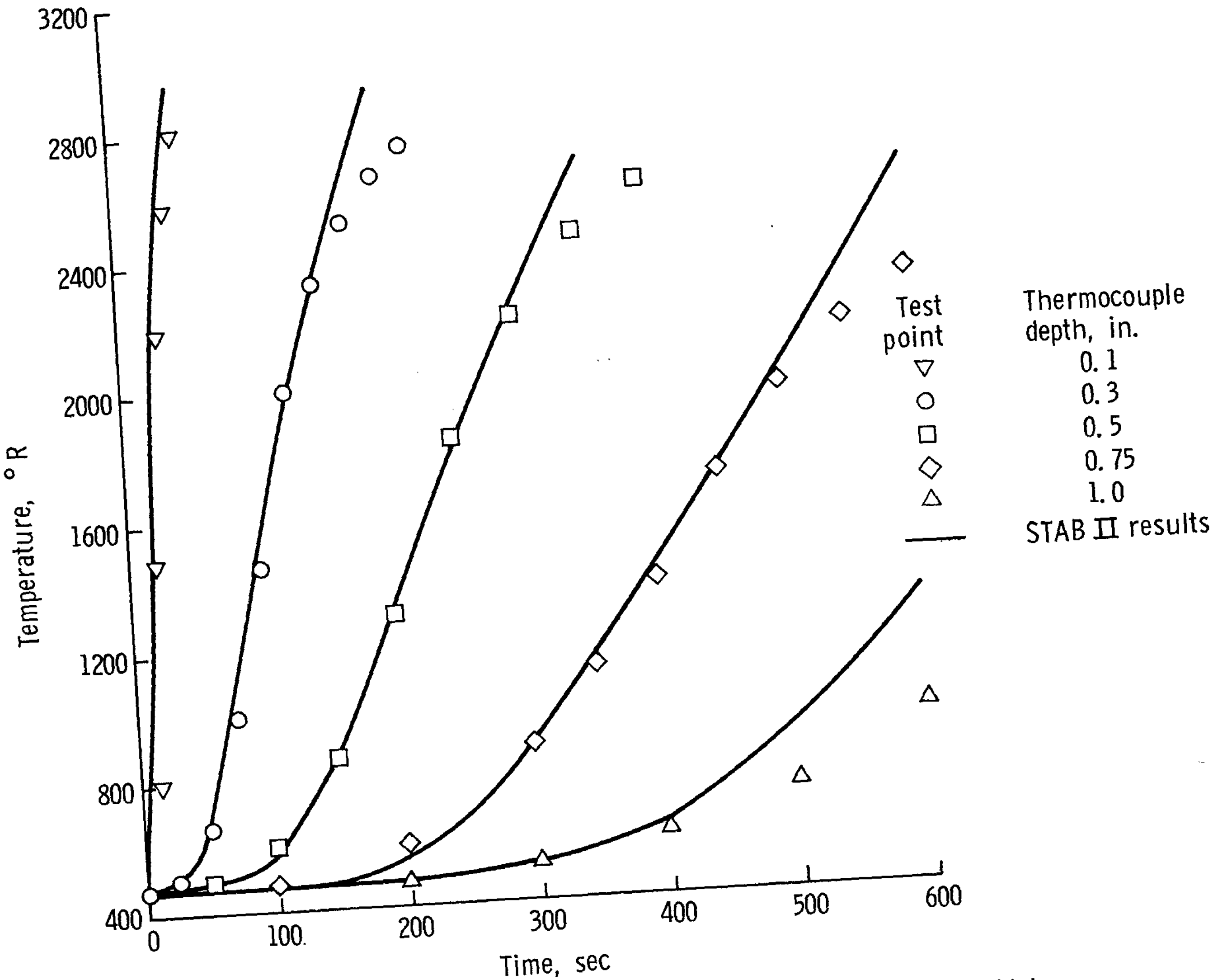



Figure 7. - Comparison of temperature histories for typical charring ablator.

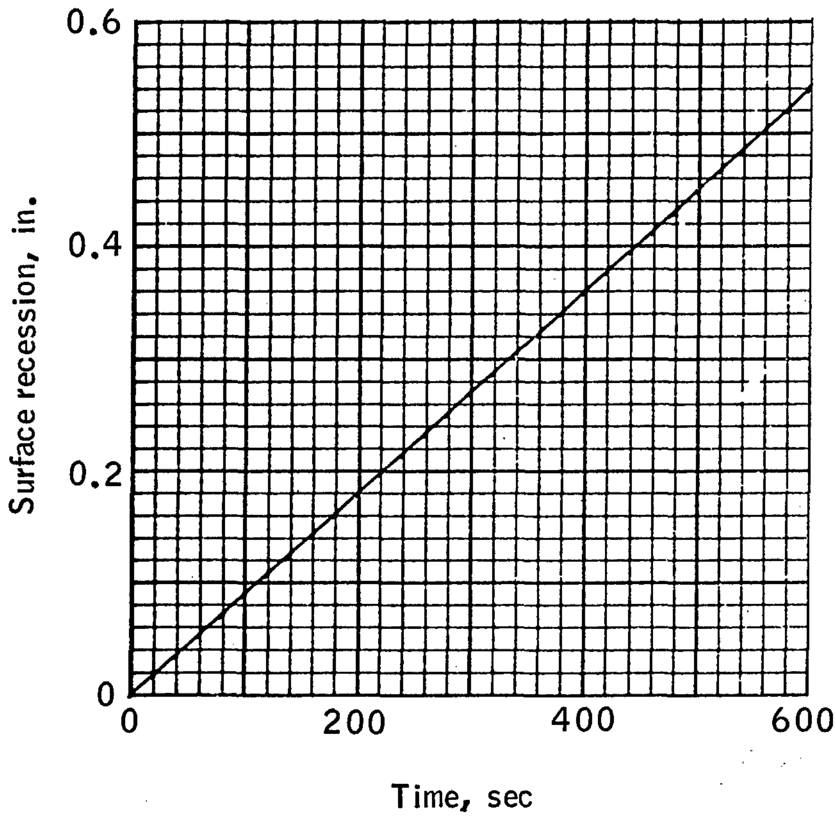



Figure 8. - Plot program surface recession curve from typical charring ablator test case.

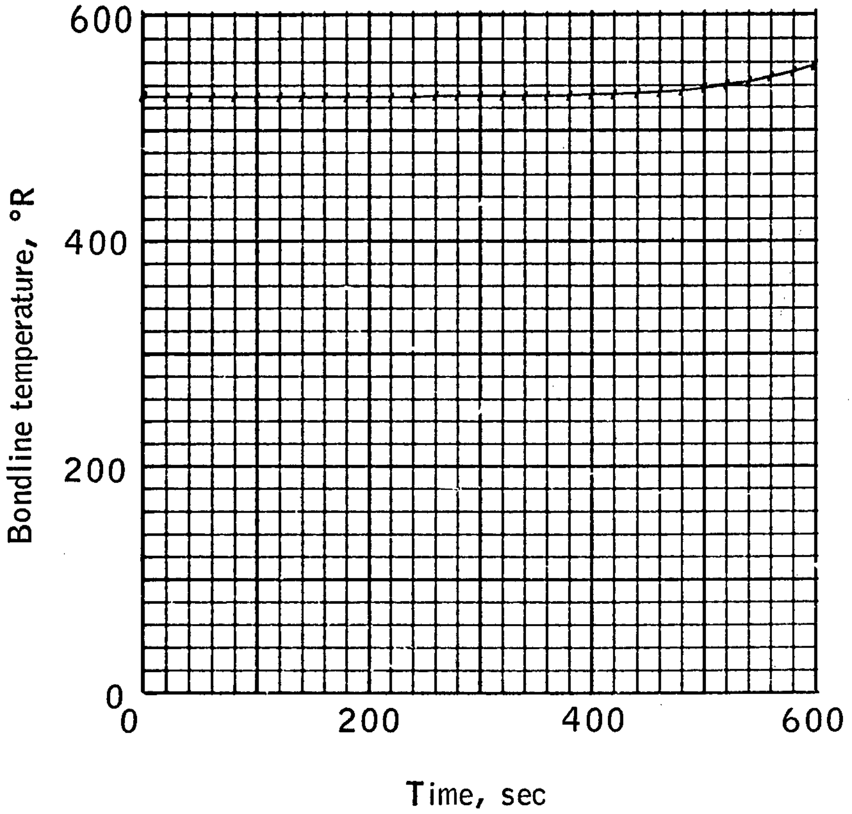



Figure 9. - Plot program bondline temperature curve from typical charring ablator test case.

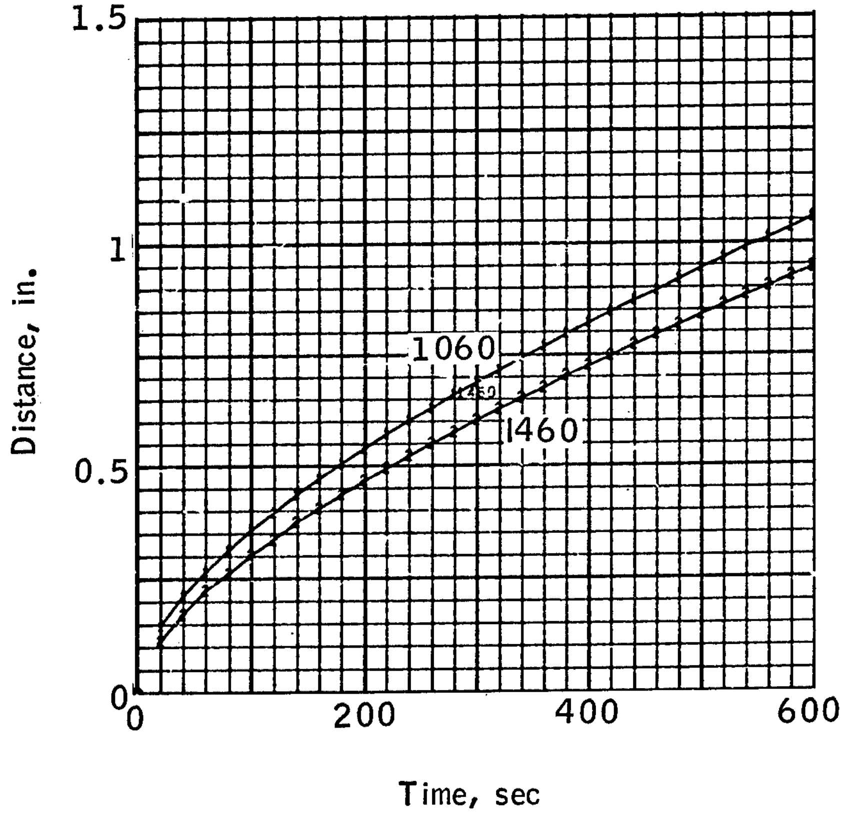



Figure 10. -Plot program 1060°R and 1460°R isotherm curves from typical charring ablator test case.



NASA-Langley, 1965 S-91